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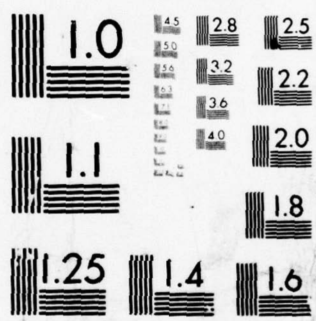

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ANNAPOLIS, MARYLAND

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DEPARTMENT OF THE NAVY
United States Naval Academy
Annapolis, Maryland 21402

Division of Engineering and Weapons

Report No. EW-16-79

6 THE STATUS OF NAVAL SEAKEEPING RESEARCH,

10 Edward V./Lewis*

11 October 1979

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In particular, it is believed that the designer needs guidance as to the influence of alternative ship proportions and other basic hull characteristics on the period-length ratio, $T_n/(L/g)^{1/2}$ (where T_n is the natural period of oscillation in any mode under consideration, L is length and g is the acceleration of gravity) and how this in turn affects ship motions in waves. For conventional mono-hulls in head or bow seas, for example, it is usually desirable to be able to operate in the sub-critical speed range in order to avoid severe synchronous pitching. Hence, it has been found (Lewis, 1955) that the limiting speed-length ratio, $v/(gL)^{1/2}$, for avoiding severe pitching, wet decks and slamming in irregular seas generally increases as the speed-length ratio reduces.

Since it may be difficult to determine the natural periods in pitch and heave by calculation or by oscillating a tank model, the effective period may be established by plotting results of systematic model tests in the form of motion amplitude vs. frequency of encounter, where frequency is varied by changing speed while wave length remains a constant parameter. The encounter frequency at which the peak amplitude occurs may be considered the effective natural frequency with this form of plotting. (Note that if wave length is varied while speed remains constant, the geometrical effect of wave length/ship length confuses the issue). Although the designer also needs guidance regarding other effects of varying ship characteristics on seakeeping, it is believed that these period-speed relationships are of primary importance.

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A survey is made of developments in seakeeping research since the Workshop in Annapolis in 1975 on Seakeeping in the Ship Design Process. Recommendations are made for the most urgently needed research to accelerate the application of seakeeping knowledge to improved ship design.

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EXECUTIVE SUMMARY*

Introduction

Since the pioneering work of St. Denis and Pierson in 1953 and of B. V. Korvin-Kroukovsky in 1955 a great deal of research has been done on seakeeping, and knowledge in the field has greatly increased. Yet it is difficult to identify improvements in ship performance that can be directly attributed to this increase in knowledge. For both merchant and naval ships questions have arisen as to how to apply the new knowledge to practical improvement in the design of ships of all kinds.

A workshop on Seakeeping in the Ship Design Process was held at the U. S. Naval Academy in July 1975, whose goal was "to formulate an action plan for developing and integrating criteria of seakeeping into the ship design process." The object of this report is to survey the progress in seakeeping knowledge since then, particularly as applied to naval ships, and to offer recommendations regarding the most urgently needed research to encourage its application to design. The emphasis is on conventional surface ships rather than high-performance craft that require their own special treatment.

Overall Status

A survey of the state of the art for evaluating the seakeeping qualities of ships reveals a broad foundation of basic principles, an impressive structure of theoretical techniques for predicting ship behavior, extensive but scattered experimental verification, efficient facilities and techniques for direct experimental evaluation of seakeeping performance, and a relatively meager body of data on full-scale performance. Gaps are revealed in the theory, particularly in areas where linearity cannot be assumed, and these gaps are discussed in the report. But the obvious imcompleteness of systematic experimental research and full-scale correlation is more serious, and practical design applications are still inadequate.

It appears that we are in danger of following the Greek philosopher's predilection for armchair science, with insufficient contact with the

*This summary is primarily a condensation of Chapters 1 and 6 of the main report.

real world. Today this tendency takes the form of:

- A failure to define the practical goals of seakeeping research on the basis of systematic measurements and observations aboard ships at sea.
- An over-reliance on computers, which sometimes leads to a confusion between computer solutions and reality.
- Insufficient emphasis on directed engineering research, in contrast to a pure-science approach.

Accordingly, it appears that, as Professor Korvin-Kroukovsky found in 1955, we are again in need of the application of vigor, even perhaps at the expense of rigor, in order to direct our seakeeping R and D toward practical goals.

A fruitful approach to an evaluation of current seakeeping research needs is to consider carefully the objectives of such research. In general it may be stated that the objective is to improve the performance of ships in rough seas — or to reduce the environmental degredation of mission effectiveness — by means of better design and operation. Hence, to be specific, the first need is for suitable criteria by which to evaluate performance.

Criteria of Seakeeping Performance

Although some useful work has been done on this subject, it is complicated by the fact that criteria depend greatly on the mission(s) that each ship is called upon to perform. Furthermore, there is a disappointing scarcity of data on numerical values of performance criteria. Some criteria have not even been clearly identified, as for example the considerations determining needed course-keeping and maneuvering capabilities in rough seas. Unless criteria can be clearly identified and numerical limits specified, further real progress in seakeeping performance is impossible. Hence, there is clearly a need for simple but widespread instrumentation on actual ships in service to provide direct correlation between measurable quantities and performance, i.e. to quantify seakeeping performance. The objective proposed here is simply to provide a link between ship behavior and human performance, between measured quantities and subjective judgment. Hence the

instrumentation should be simple and should be a permanent installation primarily for the use of operating personnel, but indirectly of value to researchers and designers.

Evaluating Seakeeping Performance

Returning to the question of objectives of seakeeping research, assuming that performance criteria will become available, the second need is for better means of predicting and evaluating performance in the design stage. Good progress has been made in this direction, but certain specific areas are in need of special attention:

- Prediction of shipping water, and calculation of local loads on bow flare.
- Prediction of slamming, and calculation of local loads.
- Prediction of rolling and design of anti-rolling devices.
- Determination of added power as a function of heading, as well as speed and wave height.
- Evaluation of steering and avoidance of broaching.

Combined theoretical and experimental approaches to these problems are needed, as discussed in the report.

The most promising theoretical approach is the selective application of elements of second order theory. A complete, rigorous non-linear theory of ship motions would be too complicated and wasteful of computer time for practical use. But in this report a number of examples are given of partial application of non-linear elements to some of the above problems.

Meanwhile, more sophisticated facilities and experimental techniques for direct evaluation of seakeeping performance can be used in routine design evaluation of critical aspects of seakeeping behavior, such as those mentioned above. Tests in irregular head seas with precisely specified wave spectra can be promptly analyzed by digital computer, and facilities for oblique sea tests are expanding.

But numerical predictions of performance are not enough. Procedures are needed to evaluate designs in terms of overall environmental

operability. Consideration must be given to the various missions a ship may be called upon to perform, their relative importance and the sea conditions in which they are to be carried out. An index is then needed of the effectiveness of the ship in carrying out those missions in the stated environmental conditions.

Finally there is a need to relate mission effectiveness to acquisition and operating costs. On the one hand such benefit/cost studies will provide guidance as to how far to go in improved seakeeping qualities. On the other hand they will provide some indication of the gains to be expected from considering seakeeping early in the design and of spending money on seakeeping research.

Computers

As for the trend toward excessive dependence on computers, computer solutions can be of great value, but only if their limitations are clearly stated and recognized. Furthermore, continual efforts must be made to check and verify the theories used in computations. In general, model experiments under controlled conditions provide the best method of checking theories pertaining to ships motions, since the difficulties of obtaining accurate full-scale data simultaneously on both ship response and on environmental conditions are close to insurmountable. Experiment alone can only answer specific questions for a specific ship design; theory alone is always suspect. But theory and experiment together can lead to steady progress: experiment verifies theory and theory generalizes experiment.

High Priority Research Needs

Throughout the survey of seakeeping research, as presented in Chapters 2-5, numerous gaps in our knowledge have been noted and suggestions for further research made. Most of these research needs are already well known, and many will be addressed in the normal course of ongoing research. Hence, the emphasis here is on high priority projects, research that is urgently needed to accelerate progress toward the goal of effectively applying seakeeping principles to the design of more efficient ships.

A summary follows of the high priority research projects recommended in Chapter 6.

1. Verification of Hindcast Techniques

Because of the potential value to designers of wave hindcast techniques, such as those in operation at the Fleet Numerical Weather Central, Monterey, it is essential that extensive, routine verification be carried out. This can be done on the basis of:

- Direct one-to-one comparisons of wave spectra obtained from wave measurements with hindcast spectra for the same location and time.
- Statistical comparisons of histograms of wave heights and periods obtained by observations and from hindcasts.

2. Wave Measurements

There is a continuing need for more systematic recording of ocean waves, both for use in verifying wave hindcast procedures (above) and for providing direct information on waves in locations of unusual sea severity. Moored buoys are suitable for these purposes, and the following tentative buoy locations were suggested by Hoffman and Walden (1977),

a) North Atlantic (Grand Banks, Faraday Sea Mount).
b) Near entrance to English Channel.
c) North Pacific (south of Aleutians).
d) Off coast of South Africa.

3. Simplified Procedures

A computer calculation procedure for basic ship motions (RAOs) should be developed for use in early pre-feasibility and feasibility studies before details of hull form and weight distribution have been established. It should be simplified for economy in routine use, but should be capable of accurately evaluating the effects of changes in:

- Ship dimensions.
- Displacement and weight distribution.
- LCB and LCF (transom width).
- Type of sections (U or V).

4. Non-linear Theory

Selective applications of non-linear approaches to ship motion theory are needed in order to obtain better practical solutions to problems such as shipping water, slamming, control of motions and added resistance — as discussed subsequently.

Experimental verification of new theoretical developments is essential.

5. Shipping Water

Combined theoretical and experimental research is needed to develop improved methods of predicting:

- Wave refraction effects as a result of bow motions, including influence of above-water hull form (flare).
- Magnitude and duration of vertical component of hydrodynamic pressure on above-water hull (flare) at water entry.

It is assumed that static bow wave build-up resulting from ship's forward motion is already fairly well understood.

6. Slamming

Although the basic rationale for predicting the occurrence of bottom slamming and estimating magnitude and duration of local pressures has been developed there are a number of important gaps to be filled:

- Survey of available theory and data on the effects of section shape.
- More complete accounting for effects of forward speed and angle of impact.
- Extension to appendages such as sponsons.

7. Control of Motions

Advances in non-linear theory (Item No. 4) should make it possible to improve the design of high-speed ships for better course-keeping and control of rolling. One of the big problems is that of yaw-roll coupling, but the need is not simply for means of reducing the effect of steering on roll (or heel) but to make a bold approach to using the rudder to reduce rolling. The goal is to be able to design hull, appendages, rudder, steering gear and automatic control system to achieve:

- Automatic steering in severe following and quartering seas that is superior to manual steering.
- Elimination of yaw-heel effects and significant reduction of roll as well.

8. Shipboard Instrumentation

A simple instrumentation package should be developed for mass production and ready installation on all types of naval vessels. Its main purpose would be to display numerical values of important ship responses for correlation with degree of success in carrying out various missions under rough sea conditions. The data would be displayed in the form of short-term averages (or extreme values in a stated period), so that displays are not rapidly changing. The actual choice of sensors and their locations would vary with ship type and mission.

After determining a suitable form of display, a standard package should be designed and a trial installation made for evaluation on a representative ship.

9. Combatant Capability Assessment (CCA)

Trial applications of CCA techniques should be made to determine the degredation of performance of several specific ships in rough seas when engaged in several missions, such as ASW and missile launching. By assuming different sea states, ship speeds and headings, trends could be determined between mission performance and critical ship responses, such as:

- Accelerations
- Angles of roll
- Hull deflection
- Course keeping

The principal purposes would be to determine the typical influence of seakeeping on combatant capability and to clarify the relative importance of the above responses as seakeeping criteria, as well as perhaps to reveal some new, overlooked criterion.

10. Evaluation Procedures

Various procedures for evaluating ship seakeeping performance

(environmental operability) have been proposed and developed, but none have been generally agreed upon and accepted.

A detailed investigation is needed of the application of these different approaches to specific design problems for different ship types and missions. After extensive discussion among designers and researchers, some tentative guidelines should be developed as to suitable procedures to be used for different ship types on various missions.

11. Performance vs Cost

Benefit/cost studies should be carried out for a number of typical cases, involving trade-offs between overall mission effectiveness in all weathers against financial outlay or life-cycle cost. The objectives would be to:

- Obtain direct indications regarding the value or importance of seakeeping research and of applying seakeeping principles early in the design process.
- Develop a procedure that can be routinely applied to new designs in the feasibility and pre-feasibility stages.

Second Priority Research

A list of important but less urgent areas of research is given at the end of Chapter 6.

THE STATUS OF NAVAL

SEAKEEPING RESEARCH

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PREFACE

An important "Workshop" on Seakeeping in the Ship Design Process was held at the Naval Academy in 1975. Discussions at that time, in which the author participated, led to some definite recommendations regarding needed research directed toward incorporating seakeeping theory and knowledge into the design process for naval ships. An assessment of progress in this direction would appear to be timely and useful to the Navy. In addition, Panel H-7, Seakeeping, of the Hydrodynamics Committee, SNAME, has expressed a need for a "critical review of the field of seakeeping which will reveal what is lacking in our knowledge and what are the difficulties in the way of successful solutions to the problem."

Accordingly, it was arranged that the author would undertake such a survey of seakeeping research from the Naval viewpoint as his major project while serving as Navsea Research Professor at the U. S. Naval Academy during the year 1979. The object of the study has been to survey recent progress in seakeeping research, including current projects underway, and make recommendations regarding new projects needed, with their priorities. It has involved interviewing individuals and groups in the Navy engaged in seakeeping research and application to design, and reviewing published papers and reports dealing with all aspects of seakeeping.

The present report giving the results of this study presents a summary of the current status of knowledge in different aspects of seakeeping, with emphasis on gaps or deficiencies requiring further investigation. It concludes with specific recommendations regarding research projects believed to be most urgently needed in relation to ship design.

The author wishes to thank the many individuals who provided information and exchanged ideas with him in the course of this survey, including the following:

Robert Keane, Edward Comstock, and Robert Johnson of NAVSEA; Eric Baitis, Ken Bales, Susan Bales, William Buckley, Geoffrey Cox, William Cummins, Seth Hawkins, M. Ochi, John O'Dea, V. Monacella, W. Morgan of

DTNSRDC; Professors Bhattacharyya, Calisal, Johnson, Munger, Salvesen of the U. S. Naval Academy; Frank Sellars, Chairman, and members, of the H-7 Panel, SNAME; Professor J. R. Paulling, University of California; R. T. Schmitke, Defence Research Establishment Atlantic (Canada); N. P. Caracostas of M. Rosenblatt & Son.

Special thanks are offered to Captain J. R. Eshman, Director of the Division of Engineering and Weapons and to Professor Peter Wiggins, Chairman of the Naval Systems Engineering Department, for providing an environment and facilities at the Naval Academy for pleasant and productive work. Finally, the competent and efficient typing of Sharon Vaughn is greatly appreciated.

Chapter 1

INTRODUCTION

BACKGROUND

The seakeeping capabilities of ships have been a concern of their designers and crews ever since ships first ventured out of sheltered waters. The problems acquired a new dimension, however, when powered vessels first were able to head directly into wind and sea instead of following the trade winds as the old square riggers had done. Not only did this result in severe pitching and heaving motions, but it led to wet decks and slamming as speed increased. With the further increase in speed of new types of high-performance craft — hydrofoil boats, surface effect ships (SES) and small-waterplane-area-twin-hull craft (SWATH) — some problems have been ameliorated and some different ones have arisen.

Furthermore, without the steadying effect of sails, powered ships had greater difficulties with rolling, and this problem was magnified by the trend toward greater initial stability for safety reasons. But the old sailing ship problem of steering in quartering and following seas — and the avoidance of broaching to — is still with us. In fact, as ship speeds have increased this problem has also increased.

Two milestone papers marked a distinct acceleration in research and understanding of the seakeeping performance of powered ships of all kinds:

Korvin-Kroukovsky, B. V. (1955), "Investigation of Ship Motions in Regular Waves," Trans. SNAME, vol. 63.

St. Denis, M., and Pierson, W. J. (1953), "On the Motions of Ships in Confused Seas," Trans. SNAME, vol. 61.

Since that time a great deal of research has been done on seakeeping, and knowledge in the field has greatly increased. Yet it is difficult to identify improvements in ship performance that can be directly attributed to this increase in knowledge. For both merchant and naval ships questions have arisen as to how to apply the new knowledge to practical improvement in the design of ships of all kinds.

The object of this report is to survey the current status of seakeeping knowledge, particularly as applied to naval ships, and to offer recommendations regarding the most urgently needed research to encourage its application to design. The emphasis is on conventional surface ships rather than high-performance craft that require their own special treatment.

WORKSHOP 1975

The logical starting point for a survey of Naval seakeeping research is the Workshop on Seakeeping in the Ship Design Process, held at the Naval Academy in July 1975, and the report prepared subsequently.* The object of the workshop was "to formulate an action plan for developing and integrating criteria of seakeeping into the ship design process."

On the basis of the work of seven task groups and general discussions, a number of significant recommendations were made. The first six dealt with policy and with items for immediate fleet support. The recommendations for research and development were as follows:

No. 7 "Develop techniques for assessing seakeeping performance in the earliest design phases."

No. 8 "Obtain data and develop design criteria relating to the sensitivity of personnel performance to the motion induced environment aboard a ship in a seaway."

No. 9 "Obtain data and develop design criteria for the sensitivity of system and equipment performance to the motion induced environment aboard a ship in a seaway."

No. 10 "Develop an atlas of the wave and wind environment by geographical area and season."

No. 11 "Develop a 'design practice' for evaluating seakeeping performance."

No. 12 "Develop a meaningful dialogue between researcher, designer and operator."

No. 13 "Develop a method for verifying predictions of seakeeping performance."

No. 14 "Conduct research directed at (a) platform survival in extreme

*"Seakeeping in the Ship Design Process," Report of the Seakeeping Workshop, Annapolis, NAVSEC and DTNSRDC, 1975.

environmental conditions and (b) platform operability in less than extreme environmental conditions."

Each of these recommendations will be discussed further in the appropriate section of this report, along with some indication of progress since the Workshop was held.

OVERALL STATUS

A survey of the state of the art for evaluating the seakeeping qualities of ships reveals a broad foundation of basic principles, an impressive structure of theoretical techniques for predicting ship behavior, extensive but scattered experimental verification, efficient facilities and techniques for direct experimental evaluation of seakeeping performance, and a relatively meager body of data on full-scale performance. Gaps are revealed in the theory, particularly in areas where linearity cannot be assumed, and these gaps will be discussed subsequently. But the obvious incompleteness of systematic experimental research and full-scale correlation is more serious, and practical design applications are still inadequate.

It appears that we are in danger of following the Greek philosophers' predilection for armchair science, with insufficient contact with the real world. Archimedes, the discoverer of what may be called the first principle of naval architecture and the inventor of many practical applications of scientific principles, is said to have "set no value on the ingenious mechanical contrivances which made him famous, regarding them as beneath the dignity of pure science..."* Today this tendency takes the form of:

- A failure to define the practical goals of seakeeping research on the basis of systematic measurements and observations aboard ships at sea.
- An over-reliance on computers, which sometimes leads to a confusion between computer solutions and reality.
- Insufficient emphasis on directed engineering research, in contrast to a pure-science approach.

Accordingly, it appears that, as Professor Korvin-Kroukovsky found

*<u>Enc</u>. <u>Brit</u>. 1967, vol. 2, p. 297.

in 1955, we are again in need of the application of vigor, even perhaps at the expense of rigor, in order to direct our seakeeping R and D toward practical goals.

A fruitful approach to an evaluation of current seakeeping research needs is to consider carefully the objectives of such research. In general it may be stated that the objective is to improve the performance of ships in rough seas — or to reduce the environmental degredation of mission effectiveness — by means of better design and operation. Hence, to be specific, the first need is for suitable criteria by which to evaluate performance.

CRITERIA OF SEAKEEPING PERFORMANCE

Although some useful work has been done on this subject, it is complicated by the fact that criteria depend greatly on the mission(s) that each ship is called upon to perform. Furthermore, there is a disappointing scarcity of data on numerical values of performance criteria. The work of Aertssen on a few particular types of merchant ships, as discussed later, is a notable exception. But the criteria for naval vessels are much more complex. Who can give even a rough indication of the correlation between accelerations at critical locations in a destroyer and the effectiveness of this man/machine system in an ASW mission, for example? Some criteria have not even been clearly identified, as for example the considerations determining needed course-keeping and maneuvering capabilities in rough seas. Unless criteria can be clearly identified and numerical limits specified, further real progress in seakeeping performance is impossible.

The importance of performance criteria was recognized at the Workshop in Annapolis in 1975. Consequently, the recommendations included research on the effects of ship motions on human peformance and on performance of machinery and equipment. Important as such studies are, it will be a long time before the answers that are needed for specific ships and missions can be synthesized from such general investigations. There is clearly a need for simple but widespread instrumentation on actual ships in service to provide direct correlation between measurable quantities and performance, i.e. to quantify seakeeping performance. It should be noted that recommendation no. 13 of the Annapolis Workshop was

to "establish a follow-up quality assurance procedure for obtaining full-scale inputs for evaluating seakeeping performance for (a) providing feedback to the designer and the operator and (b) improving and revising design criteria."

Detailed recommendations regarding such quantifying instrumentation will be given subsequently, but at this point it is essential to emphasize that there are several different goals for shipboard instrumentation. One is to obtain research data on specific problems, involving either long-term collection of statistics or short-term, intensive measurements of ship responses, along with ocean wave measurements, if possible. The objective proposed here is distinctly different, since it is simply to provide a link between ship behavior and human performance, between measured quantities and subjective judgment. Hence the instrumentation should be simple and should be a permanent installation primarily for the use of operating personnel, but indirectly of value to researchers and designers.

A third objective for shipboard instrumentation is oriented entirely toward ship operation: providing warning of severe motions, accelerations or stresses that might lead to damage to the ship, its personnel or its equipment. Such monitoring instrumentation should also be simple, as discussed subsequently in this report.

EVALUATING SEAKEEPING PERFORMANCE

Returning to the question of objectives of seakeeping research, assuming that performance criteria will become available, the second need is for better means of predicting and evaluating performance in the design stage. Good progress has been made in this direction, but certain specific areas are in need of special attention:

- Prediction of shipping water, and calculation of local loads on bow flare.
- Prediction of slamming, and calculation of local loads.
- Prediction of rolling and design of anti-rolling devices.
- Determination of added power as a function of heading, as well as speed and wave height.
- Prediction of effectiveness of automatic steering

Combined theoretical and experimental approaches to these problems are needed, as discussed subsequently in this report.

But numerical predictions of performance are not enough. Procedures are needed to evaluate designs in terms of overall environmental operability. Consideration must be given to the various missions a ship may be called upon to perform, their relative importance and the sea conditions in which they are to be carried out. An index is then needed of the effectiveness of the ship in carrying out those missions in the stated environmental conditions. This subject is discussed in chapter 5.

Finally there is a need to relate mission effectiveness to acquisition and operating costs. On the one hand such benefit/cost studies will provide guidance as to how far to go in improved seakeeping qualities. On the other hand they will provide some indication of the gains to be expected from considering seakeeping early in the design and of spending money on seakeeping research.

THEORY

As for the trend toward excessive dependence on computers, we sometimes encounter situations in which a computer model is claimed to be "as good as" the real thing. This obviously cannot be true, since the computer representation can be no better than the theory on which its programming is based and the empirical coefficients that are inserted. Computer solutions can be of great value, but only if their limitations are clearly stated and recognized. Furthermore, continual efforts must be made to check and verify the theories used in computations. In general, model experiments under controlled conditions provide the best method of checking theories pertaining to ships motions, since the difficulties of obtaining accurate full-scale data simultaneously on both ship response and on environmental conditions are close to insurmountable. Experiment alone can only answer specific questions for a specific ship design; theory alone is always suspect. But theory and experiment together — as shown by Korvin-Kroukovsky and others — can lead to steady progress: experiment verifies theory and theory generalizes experiment.

An important sequence in the development of ship motion theory was the bold statement of strip theory by Korvin-Kroukovsky, in which vigor rather than rigor was stressed, followed by the definitive experimental work of Gerritsma. The latter did not consist simply of overall comparisons of calculated and measured motions, but made separate evaluations of different aspects of the theory:

- Exciting forces (by restrained model tests in waves).
- Motion-related forces (by forced oscillation tests in calm water).
- Accuracy of theoretical determination of coefficients.

As a result of these tests it was established that, for the type of slender fine-ended, moderate-speed ship investigated, the theory was basically sound, but that refinements would be worthwhile, particularly in allowing for forward speed effects and for the calculation of coefficients for unusual section shapes and/or for certain ranges of frequencies. Fortunately, progress in all these areas has continued during the intervening years.

Again in the area of ocean wave data there is a tendency to prefer the use of idealized wave spectral formulations instead of statistical collections of actually measured spectra. And the valuable technique of "hindcasting" spectra from observed winds by means of complex computer models requires extensive and continuing verification against real measurements before it is relied on too heavily.

ENGINEERING RESEARCH

Today there is clearly a need for the selective application of elements of second order theory to answer specific questions of practical operation. A complete, rigorous non-linear theory of ship motions would be too complicated and wasteful of computer time for practical use. But later on in this report a number of examples will be given of partial application of non-linear elements:

- Broaching in quartering and following seas.
- Shipping water in bow seas.
- Added resistance in waves.

Further developments along these lines, involving scientific and engineering judgment, and experimental verification, are believed to be more urgent than pursuing detailed, complex advanced theories. In short, vigor rather than rigor remains our most urgent need in research.

Meanwhile, more sophisticated facilities and experimental techniques for direct evaluation of seakeeping performance can be used in routine design evaluation of critical aspects of seakeeping behavior, such as those mentioned above. Tests in irregular head seas with precisely specified wave spectra can be promptly analyzed by digital computer, and facilities for oblique sea tests are expanding.

PLAN OF REPORT

In view of these introductory comments it is not surprising that the research recommendations in this report will emphasize work on techniques of evaluating seakeeping performance, with the help of shipboard instrumentation, and on experimental confirmation of theoretical developments.

The plan of the report is first to review the state of the art relative to seakeeping knowledge applicable to design, under the headings of Environment, Ship Motions, Derived Responses, and Applications, and second to identify and describe areas in which research is most urgently needed. Consequently, no attempt is made to survey the entire status of seakeeping knowledge and research. For such a broad overview, reference can be made to comprehensive surveys such as,

- "Environmental Wave Data for Determining Hull Structural Loadings," by Hoffman and Walden, Ship Structure Committee Report SSC-268, 1977.
- "A Summary of Wave Data Needs and Availability," Ship Research Committee, National Research Council, Washington, D. C. 1979.
- Report of Seakeeping Committee to 15th ITTC, Paris, 1978, with appendices (also reports to previous conferences).
- Report of Seakeeping Committee to 18th ATTC, Annapolis, MD, 1977.
- "The Dynamics of Marine Vehicles and Structures in Waves," Proceedings of International Symposium, University College, London, 1974.
- "Seakeeping 1953-1973," Proceedings of Technical and Research Symposium S-3, SNAME, Webb Institute of Naval Architecture, October 1973.
- "Seakeeping Theories: What is the Choice?" by Odabasi and Hearn, Trans. NECI, vol. 94, 1977-78.

Other surveys will be mentioned in individual sections of the report.

HIGH-PERFORMANCE CRAFT

High-performance craft, such as SES, hydrofoils, SWATH, planing boats, etc., have not been dealt with explicitly in this report. It is not that they are not considered to be important, but that they have already been dealt with rather extensively in recent years. Mention should be made particularly of the following references:

Mandel, P. (1960), "Subcritical and Supercritical Operation of Ships in Waves and the Coincidence of Maximum Damping," Journal of Ship Research, June.

Meeks, T. L., Capt. (USN), Graham, C., CDR (USN), and Hu, R. C. (1976), "The Advanced Naval Vehicle Concept Evaluation," AIAA/SNAME Advanced Marine Vehicles Conference.

Olson, S. R., CDR (USN) (1978), "An Evaluation of the Seakeeping Qualities of Naval Combatants," Naval Engineers Journal, vol. 90, Febr.

Birmingham, J. T., Jones, H. D., Hadler, J. B., and Lee, C. M. (1974), "Ocean Catamaran Seakeeping Design, Based on the Experience of USNS Hayes," Trans. SNAME, vol. 82.

Eggington, W. J., and Kobitz, N. (1975), "The Domain of the Surface-Effect Ship," Trans. SNAME, vol. 83.

Savitsky, D., and Brown, P. W. (1976), "Procedures for Hydrodynamic Evaluation of Planing Hulls in Smooth and Rough Water," Marine Technology, Oct.

Graham, C., LCDR (USN), Fahy, F., and Grostick, J. (1976), "A Comparative Analysis of Naval Hydrofoil and Displacement Ships," Trans. SNAME, vol. 84.

Meyer, J. R. (1977), "A Comparison of Several Hybrid Surface Ship Concepts," Naval Engineers Journal, April.

Lee, C. M., and Curphey, R. M. (1977), "Prediction of Motion, Stability, and Wave Load of Small-Waterplane-Area, Twin-Hull Ships," Trans. SNAME.

Reference should also be made to a number of papers presented at the AIAA/SNAME Advanced Marine Vehicles Conferences held in 1967, 1972, 1974, 1975, 1976 and 1979.

Chapter 2

ENVIRONMENT

THEORY

The aspect of ships' environment that is of basic concern to seakeeping is of course the surface waves of oceans, seas, lakes, etc. Much has been learned in recent years, and much remains to be learned. A basic theory has been developed which provides a means for describing the complex and irregular surface of the sea. In order to utilize the theory effectively a vast amount of organized observational data is needed. These two aspects of our knowledge of the sea will be discussed in turn.

The techniques of generalized harmonic analysis have provided the basis for a mathematical model of ocean waves. In its simplest form it assumes a normal or Gaussian stochastic process that — over periods of time that are long enough for analysis but not so long that significant changes in weather occur — is stationary over time and space, i.e. statistical properties remain unchanged. The model assumes that at any location and at any instant the surface of the sea is the result of the linear superposition of progressive harmonic wave trains of an infinite number of frequencies and directions in *random phase*. Hence, the sea can be described by an amplitude or variance spectrum as a function of frequency and direction (St. Denis and Pierson, 1953). (See p. 17).

From the viewpoints of ship design and ship operation the theory appears to be highly satisfactory for descriptive purposes, not only for the open sea, but for shoal water, conditions of limited fetch, etc. Its only limitation appears to be extreme conditions (very high winds or very shallow water) where extensive wave breaking occurs. Moderate breaking will cause local departures from the mathematical model, but the effect of wave breaking on the overall wave pattern will be reflected in the shape of the resulting spectrum of the sea.

The theory for calculating or predicting surface wave spectra from known or predicted wind fields is also well developed and is advancing rapidly. At any given location and time, however, the wave pattern — and hence spectrum — depends not only on the local wind field but on previous winds and on waves generated by winds in other areas. Hence, the forecasting of wave spectra requires knowledge of wave propagation

and wave decay as well as wave generation. Theories for these, too, are well developed, and mathematical models for entire oceans — as the North Atlantic and North Pacific — are in routine operation (Lazanoff and Stevenson, 1975). These theories take account of directional properties of wave spectra and of the combined effect of two or more distant storms.

Here we are faced with one of the dangers mentioned in the Introduction: inadequate experimental or full-scale verification. A certain amount of effort has been directed toward comparison of forecast and measured spectra, with results that can best be described as encouraging but inconclusive. It is important that such evaluations be continued on a large scale and that results be used to further refine and improve the basic mathematical model, as well as to establish its current precision.

DATA

Available ocean wave data for use in ship design and operation fall into several categories:

- Observed data collected from ships at sea, usually in the form of significant height and some characteristic period
- Wave measurements (weather ships, fixed platforms, buoys) from which spectra can be calculated (directional properties are rarely known)
- Systematic forecasts (or hindcasts) of wave spectra from forecast or reported wind data. Directional properties are included.

Observed data. These are the most extensive and cover almost all navigable seas of the world. They are usually in the form of tabulated frequencies of occurrence of different combinations of significant wave height and period (Hogben and Lumb, 1967). For practical use of these data in problems of ship design and operation it is necessary to match the various combinations to representative sea spectra. This has been done in two ways:

- Use of a general spectrum formulation, such as that of Bretschneider — adopted by ISSC — that utilize wave height (H) and period (T) as parameters (ISSC, 1970).
- Use of "families" of measured spectra having the desired values of H and T (Hoffman, 1975; Hoffman/Miles, 1976; Hoffman/Walden, 1977).

The former is the simplest and most convenient; for some purposes it is sufficiently accurate. The latter is less convenient but is believed to be more accurate. Studies have shown on the one hand that there are large variations in spectral shape not accounted for by a simple change in T alone. (Some of these variations can be described by the higher moments of spectral areas about the 0-frequency axis, and by providing for double peaks.) On the other hand there are significant variations of spectral shape with severity of the sea (wave height) (Ferdinande, 1977). There are also changes in shape under fetch-limited and shoal-water conditions, and attempts have been made to develop formulations to describe the spectra under these conditions, e.g. the JONSWAP formulation (Ewing, 1974). The attraction of the formula approach is its simplicity for use in computer programs for evaluating ship behavior. A covariance method of selecting a spectral family has been developed by Chen and Hoffman (ISSC, 1979).

Since in either of the above approaches no direct information is given regarding directional properties of the sea, short-crestedness can be provided for approximately by assuming a reasonable "spreading function." However, this still does not take care of the frequent existence of cross-seas resulting from the superposition of waves from two or more storms, or for combinations of storm seas and swell (from a distant storm).

When attempts have been made to account for irregular shapes, e.g. double humps, by superimposing storms (Ochi and Hubble, 1976) no account has been taken of the differences in predominant wave direction of these storms. Hence, these more complex formulations still do not provide satisfactory realism.

When ideal spectra described by mathematical formulas are used, attention is now being given to the problem of spectrum "tails." (St. Denis, 1976). The area under the spectrum, from which significant height is determined, depends on where the integration is cut off at the high-frequency end (Bishop and Price, 1978).

Again it appears that the urge for comprehensive computer solutions to design and operating problems has lured us into adopting artificially simple descriptions of the complex wave environment. For some purposes these idealizations may may be useful, but the danger is that they become accepted and set in concrete, and that further progress is thereby stifled.

Wave measurements. These have been made at only a limited number of locations and therefore cannot be directly applied to the usual problems of ship design and operation. Rather they — and spectra calculated therefrom — have been used in connection with the previously described observed data in two ways:

- As a means of checking the theoretical formulations.
- As a source of wave spectral families to be used in place of the above formulations.

The potentiality exists for making more extensive use of large moored buoys at critical ocean locations to provide systematic ocean wave measurements that can be analyzed on shore. Some areas of special importance are: the vicinity of the Cape of Good Hope, off Cape Horn, at the edge of the Continental Shelf at the entrance of the English Channel, etc. As a matter of fact, a data buoy has recently been deployed at the last location (The Naval Architect, May 1978, p. 103).

Looking to the future, techniques for systematic wave measurement from orbitting satellites are under development and may be able to provide useful data before long.

It is a curious fact that students of ocean waves have made so little use vertical acceleration data obtainable directly from wave buoys, rather than double integrating to obtain displacements. An acceleration spectrum is equivalent to a wave-slope spectrum*, and it is wave slope that figures prominently in wave generation theories. Furthermore, a wave slope spectrum is much simpler to describe mathematically than the amplitude or variance spectrum. In addition wave slope is more significant than amplitude for some responses — as pitch, roll, relative bow motion, wave bending moment. The formulations discussed in the previous section, which attempt to describe wave spectra, are all expressed in complicated exponential form. Some study of the use of acceleration (wave slope) spectra is recommended.

Hindcast Wave Spectra. As previously mentioned, spectrum forecasting is the direct result of advancing theories of wave generation and propagation.

*If $S(\omega)$ represents the ordinate of a typical variance spectrum, the ordinate of a slope spectrum is $\frac{2S(\omega)}{g^2/\omega^4}$.

They are of increasing usefulness for ship design and operation. Of particular value is the comprehensive system developed and in operation of FNWC, Monterey, for the North Atlantic, North Pacific Ocean, and the Mediterranean Sea (Lazanoff and Stevenson, 1975) — to be extended to the southern hemisphere. In this activity, "forecast" spectra are those calculated from forecast wind fields primarily for operational use by mariners, while "hindcast" spectra are calculated from the actual reported wind fields. The latter are of particular value for ship designers, if carried out systematically and reduced to a useable format. The principal advantages of the hindcast spectra for design use are:

- Wide coverage of the world's oceans.
- Availability of input wind data for many years in the past.
- Inclusion of directional properties of seas and cross seas.

There are certain limitations to be considered:

- Data are calculated rather than measured, a disadvantage that can be overcome by systematic and extensive comparison with actual measurements.
- Accuracy is of necessity reduced in areas where wind observations are scarce.
- Range of wave frequencies covered may not be adequate for all purposes.

At this point recommendation no. 10 of the Annapolis Workshop (NAVSEA 1975) may be quoted:

"Develop an atlas of the wave and wind environment by geographical area and season."

"Such an atlas will be based on wave descriptors which are meaningful to both ship operators and ship designers; it will be suitable for use in the early phases of ship design. This atlas will provide the environmental data for translating seakeeping performance requirements in specified operating areas and seasons into specific design criteria."

The best basis for such an atlas appeared to be the FNWC wave hindcast model, and consequently a comprehensive project for developing a worldwide Hindcast Climatology was undertaken some time ago as a joint DTNSRDC/FNWC project (Bales and Cummins, 1977). An initial report is to be published soon by the National Weather Central covering the following parameters for 50 locations in the North Atlantic over a period of 5 or

6 years:

- Wind speed and direction.
- Wave spectral data for both primary and secondary directions,

    Significant height.
    Characteristic period.
    Direction.
    Spectral width.
    Angular spread.

In addition, statistical data will be given on wave steepness and wave persistence or duration. The actual numerical spectra (180 numbers covering 15 frequency bands and 12 directions) will be kept in a computer file at DTNSRDC.

Later publications will cover additional years in the North Atlantic and will then be extended to the North Pacific, Mediterranean Sea — and eventually to the South Atlantic.

Meanwhile, efforts must be made immediately to reduce the mass of hindcast spectra that threatens to overwhelm us to more manageable form. It is recommended that statistical data be derived covering essential parameters of the primary and secondary (if any) systems described by these spectra, such as:

- Overall significant wave height and average period.
- Direction of dominant storm wave system.
- For both primary and secondary storms — significant height and average period.
- Angle between primary and secondary storms.
- Contribution of secondary system to significant wave height, %.

From statistical data on the above parameters it should be possible to generalize on assumptions regarding wave spectra for any ocean route and season for ship design purposes.

Hindcast procedures are also available for the Great Lakes, but results have not yet been made available in the complete form discussed above.

NEEDED RESEARCH

Hence, by way of summary, it seems clear that several continuing activities are needed:

a) Direct measurement of waves at critical locations by means of moored buoys, and routine spectral analyses, over long periods of time.

b) Extensive, routine verification of wave hindcast theory by observation and measurement of waves.

c) Refinement and improvement of wave prediction and hindcast techniques.

d) Continued preparation and distribution of worldwide wave data on observations, measured spectra, hindcast spectra, and statistical parametric data on the latter.

e) Extension of studies to oceans, seas and lakes (e.g. the Great Lakes) not so far adequately covered – particularly to the southern hemisphere.

Chapter 2

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SHIP MOTIONS

Chapter 3

INTRODUCTION

Since Korvin-Kroukovsky's (1955) bold application of strip theory to the problem of ship motions in waves, emphasizing vigor in preference to rigor, a great deal of progress has been made in the direction of greater rigor. This has led to the inclusion of additional terms in the equations of motion, some of which have improved the correlation with experiment and some have not. The effects of the ship's hull on wave diffraction have been included. There have also been improvements in the precision of calculating hydrodynamic coefficients, through the use of "close fit" methods.

A valuable review of the development and current status of the theory for predicting ship motions (regular waves) was given by Ogilvie and Beck (1974). They summarized the status thus:

> "Now the so-called 'strip theory' and the mathematical theory based on the slender-body idealization give essentially the same results. For the most part, these results are fairly accurate, at least for conventional ships. Frequency dependence of most of the important coefficients is estimated well, and wave loads, including diffraction effects, are fairly realistic. The assumed linearity of the system is confirmed over a wide range of conditions. Predictions can now be made with confidence for five degrees of freedom.
>
> "The computation of excitation forces is perhaps the least reliable aspect of current mathematical models. The validity of the theory for unconventional hulls and for non-shiplike bodies needs further experimental confirmation. Roll motion is strongly affected by nonlinear viscous effects which are introduced into the analysis empirically. Major deficiencies arise when motions are large, and it is certain that nonlinear analyses of ship motions will require major attention in the coming years."

The problem will be, as noted in the Introduction, Chapter 1, to introduce non-linear terms in a selective fashion to help solve practical problems without excessive complexity.

While refinements have continued in ship motion theory, the need has grown for other simpler approximate approaches that can be used in the early stages of design when general ship characteristics and proportions are being decided.

Along with theoretical advancements, model test facilities have expanded and techniques have been improved. Current status has been reviewed by the Seakeeping Committee, ITTC (1978). A number of additional large maneuvering and seakeeping basins, permitting testing in oblique seas, are now in operation. Most tanks, whether narrow or wide, have the capability of generating irregular as well as regular waves. Digital recording of data and spectral analysis of records by computer are usually provided.

Generally model testing has been for two purposes:

- To support and verify theory.
- To provide answers regarding the behavior of specific ship designs — particularly in areas where theoretical answers are in doubt.

The determination of the amplitudes and phase relations of the six components of ship motion in regular waves is seldom of direct usefulness in problems of ship design and operation. Even roll angle in its pure form is of less interest than the "apparent"roll angle which includes the effect of sway. The great value of the theoretical or experimental determination of the basic motions in regular waves in that they provide the "building blocks" for calculating the various derived responses discussed in another chapter — accelerations, relative bow motion, added resistance, etc.

The use of the theory of superposition permits the immediate application of motion calculations in regular waves to the prediction of ship motions — in statistical terms — in irregular seas of any desired characteristics (St. Denis, Pierson 1953). The results of 20 years' experience in the application of this technique were surveyed in an SNAME

Symposium (Panel H-7) held at Webb Institute of Naval Architecture in 1973.

At the above meeting Dr. W. E. Cummins (1974) said, "The experience of the last twenty years has demonstrated that the St. Denis-Pierson theory is a very powerful tool for predicting seakeeping performance. However, there have been found situations in which the theory tends to break down. The transfer functions may become nonlinear, either because of a very high Froude number or because of unusual hull shape. In particular, hulls with large bulbs exhibit strongly nonlinear responses. But even in the case of significant nonlinearity, useful predictions can frequently be made if the transfer functions are obtained from experimental data which exhibit these effects."

A more detailed discussion follows of theory, experiment, and comparisons between theory and experiment.

THEORY

An excellent detailed survey of the state of ship motion theory is given in a recent paper by Odabasi and Hearn (1978). They show that the principal differences among the various strip theories now in use are in methods of calculating the following:

- Wave exciting forces.
- Added mass and damping coefficients.
- Forward speed effects on vertical motions.

Quoting, "In the original paper of Korvin-Kroukovsky and Jacobs (1957) the entire approach was based on engineering judgment and various terms in the equations of motion were derived according to a somewhat arbitrary definition of the relative motion between the ship and the water particles. In the following years, improvements of the problem formulation have been proposed, both from intuitive and theoretical viewpoints. The studies of Gerritsma and Beukelman (1964) and Ogilvie and Tuck (1969) are respectively the examples of the former and latter types of considerations. One important feature of the theoretical methods was the elimination of the relative motion concept. Instead, the total motion was obtained as a sum of a radiation and a diffraction problem, cf. Haskind, (1957), Hanaoka (1959) and Newman (1965)."

"The numerical calculation of fluid reactive forces and moments, i.e. added mass/moment of inertia and wave damping, based on two-dimensional modelling have been carried out by three different types of approach. The first and the simplest was the use of conformal mapping techniques with no free surface effects.....(Lewis, 1929; Landweber and Macagno, 1957, 1959).... The second approach is the use of series of multipoles, due to Ursell (1949)...." and developed by Grim (1953), Tasai (1959, 1961) and Porter (1960). "The third approach is the use of source distributions over the hull surface which can also be attributed to Ursell (1953). The practical use of the source distribution method is due to Frank (1967), which is often referred to as the 'Frank Close Fit' method.

"Consideration of the forward speed in the coefficients of equations of motion is another source of difference between various strip theories. Amongst the available approaches, the methods of Gerritsma and Beukelman, (1964) Ogilvie and Tuck (1969) and Salvesen, Tuck, Faltinsen (1970) are representative of three different approaches for the longitudinal motions. Whereas the methods of Kaplan, Sargent and Raff (1969), Salvesen, Tuck and Faltinsen (1970) and Grim and Schenzle (1968, 1969) are respresentative of three different approaches for the lateral motions. Of these methods only Ogilvie and Tuck (1969) and Salvesen, Tuck and Faltinsen (1970) satisfy the Timman-Newman symmetry condition.

"To overcome some conceptual and practical shortcomings of the strip theory various attempts have been made to include the effects of three dimensionality. Computations, however, indicated that these corrections did not provide an improved accuracy. In fact, in a large majority of the cases the predictions worsened when the three dimensional corrections were included. Only the approach proposed by Grim (1960) appeared primising; he proposed an interesting quasi-three-dimensional method. His method, however, did not receive wide acceptance in practice because of the more complicated calculations required.

"Attempts to calculate the fully three-dimensional hydrodynamic properties of oscillating bodies on or below the free surface of liquid are not new and, in fact, calculations for simple geometric shapes have been made, cf. Havelock, (1955) and the Green function for three-dimensional

singularities have been derived, cf. Kochin (1940). The possibility of using a fully three-dimensional method as a practical means of calculation became possible after the famous paper of Hess and Smith (1962) who proposed a computer-oriented surface source distribution method for the numerical evaluation of the flow properties around arbitrary three-dimensional bodies. The development of the three-dimensional approaches has been quite slow because of the large core and computer time requirements for a meaningful numerical evaluation.......Although analytical formulations for three-dimensional calculations with forward speed have been made (Chang and Pien, 1976) to the authors' knowledge, there is no numerical result yet available."

No mention was made above of recent work by M. S. Chang (1977) in developing a method which uses three-dimensional oscillating Kelvin sources distributed over the hull surface. Good results were obtained at zero and low speed, with considerable improvement over strip theory at low frequencies of encounter.

Salvesen (1978) has developed a second-order theory for pitching and heaving which takes account of non-linear section shapes, which can be important at bow and stern.

A comprehensive mathematical model for the prediction of lateral ship motions in oblique seas was presented by Schmitke (1978). It is based on the basic strip theory of Salvesen, et al (1970), with coefficients from various sources. Particular attention is given to the estimation of roll damping, including dynamic lift an appendages. Comparison of calculations with model and full-scale data indicated generally good agreement for rolling of naval ships. Calculations of the effect of various anti-rolling devices will be discussed in another chapter.

Progress was also made in several important areas, such as motions in shallow water by Hooft (1974), and van Sluijs and Gie (1975), the behavior of high-performance craft such as hydrofoil boats (Schmitke, R. T., 1976) surface effect ships, SWATH vessels (Lee and Curphey, 1977), etc.

The David Taylor NSRDC has available a basic ship motion program YF 17 for head seas, based on the strip theory of Frank and Salvesen (1970). This has been revised by Hubble (1976) for greater convenience and accuracy (speed term for pitch damping). Computer programs for all

headings are also available, based on Salvesen, et al (1970) for mono hulls and Lee (1976) for twin-hull ships. User manuals have been prepared by Meyers, et al (1975) and McCreight and Lee (1976).

Other programs are available elsewhere, including SCORES (Raff, 1972) and MIT (Loukakis, 1970) — based on Salvesen, et al (1970).

Several limitations on the capability of the above basic strip theory ship motion calculations should be clearly stated. They do not apply:

- outside the linear range
- to very short waves
- to very high speeds
- to hulls that are not "slender."

As previously noted, the first limitation is a serious one with respect to rolling. But for the other modes of motion at moderate speeds non-linearity seldom has a significant effect for most purposes, except for unusual forms and bulbous bows.

The short-wave limitation is not serious, because short waves do not cause significant ship motions. However, it is important for calculation of short-wave forces that may excite springing, for example.

Although speed terms are included in the basic theories, additional effects at high speed are not fully accounted for. In regard to slenderness, the length/beam ratio is sometimes considered a suitable parameter. Gerritsma, et al (1974) found that experimental results agreed quite well with strip theory calculations for L/B ratios as low as 4.

Also certain cross-coupling terms, such as pitch/roll and pitch/yaw, are not included in the basic theory, an omission which may have a significant effect on lateral motions. See Chapter 4.

To facilitate seakeeping studies of existing ships, extensive computer data bases have been prepared at DTNSRDC, such as that of Baitis, et al (1974) covering the DD963, CG26, FF1052, FFG7 and FF1040 classes. These computations were based on the ship motion theory of Salvesen, et al (1970) and the data are presented in the following forms:

- RAOs; motion amplitudes per unit wave amplitude, and phase angles.
- RMS responses and spectrum peak periods for long and short-crested

seas (Bretschneider spectra)

- Time domain responses for 1/2-hr periods, derived from the response spectra.

In using such data banks for detailed seakeeping analyses, caution must be exercised regarding the same limitations of the basic theory previously mentioned.

Furthermore, response results are limited to certain idealized Bretschneider wave spectra, and therefore do not reflect any spectral shape variation other than that described by shifting of the spectrum peaks.

EXPERIMENT

Odabasi and Hearn (1978) discuss the importance of model experiments. "An important factor contributing towards the development and wider acceptance of the theory has been the model experiments. In this respect experiments conducted by Gerritsma (1957), Golovato (1959), Fancev (1961) and Dalzell (1962) may be mentioned because of their historical importance. Gerritsma (1957) initiated the combined use of theory and experiment, Golovato (1959) initiated the transient testing and demonstrated the history effect in the model response, and Fancev (1961) and Dalzell (1962) proved experimentally the validity of the transfer function approach. Systematic model experiments have also been conducted in various countries to assess the limits of applicability of various strip theories, cf. Vossers, Swaan and Rijken (1960) and Vugts (1970). Today model testing is an integral part of the seakeeping theory, and the use of modern planar motion mechanisms in model tanks has increased the capability and the accuracy of model testing techniques." See also Gerritsma (1958).

A new paper by D. C. Murdey (1979) provides an excellent statement of the goals and capabilities of experimental techniques for evaluating seakeeping performance, and describes various facilities and techniques currently in use for a variety of purposes. "It is concluded that the provision of reliable ship predictions requires the use of specialized model test facilities supported by increasingly sophisticated analysis techniques, and that in future the theory and experiment approaches will be even more closely united than has been the case in the past."

An example is the new model basin at the U. S. Naval Academy, with its sophisticated system for irregular wave generation (Anderson and Johnson, 1977) and for digital computer data analysis (Gebhardt, et al, 1977). The utilization of a finite number of discrete wave components, equally spaced in the encounter frequency domain, permits a precise numerical analysis of the response spectra with a single short run — in lieu of a statistical analysis of a number of repeated runs. Hence, a complete set of head sea RAOs can be obtained quickly by means of as many runs as speeds required.

Furthermore, the ability to produce, and repeat, any desired wave spectrum permits the direct evaluation in head (or following) seas of secondary responses, such as shipping water, slamming, added resistance and power, propeller emergence, etc. For example, a single model with alternative above water bow sections could be run to determine absolute and comparative numbers of cases of shipping water with differing amounts of forward flare and shear.

The report of the Seakeeping Committee, ITTC (1978), gives the results of a questionaire sent to model basins having seakeeping test facilities. A table gives the characteristics of model tanks, wavemakers, wave probes, controls, etc., assembled from 30 institutions covering 51 different test facilities. A few highlights:

- Approximately 25% of establishments use wide, specially built seakeeping basins
- 10 facilities reported the ability to test in shallow water
- all facilities have at least one wavemaker; 6 basins have wavemakers on two sides
- Almost all wavemakers have the capability to generate irregular waves
- data are generally digitized for analysis, the majority of tanks using off-line analysis; but on-line analysis is becoming more popular.

Studies of tank wall interference are continuing.

Recent work on wave groups (Goda, 1976) has shown that particular sequences of waves may be important. Hence, there is considerable interest

in controlling phase as well as amplitude of components in irregular tank waves in order to produce such groups. (Anderson and Johnson, 1977).

There is also interest in generating short-crested waves by superimposing two wave trains (Sugai, et al, 1975) or by placing wedges on the wavemaker (Hogben, 1978). It is understood that short-crested waves can be generated at the University of Edinburgh and are planned for the new Troudheim seakeeping basin and the tank at the Canadian Arctic Vessel and Marine Research Institute in St. John's, Newfoundland (Murdey 1979).

COMPARISONS BETWEEN THEORY AND EXPERIMENT

The Seakeeping Committee (1978) of the ITTC has recently made a comparison of ship motion calculations made by different worldwide ship model basins, each using its own standard method. Comparisons were also made with limited experimental results obtained by means of a free-running model at the Ship Research Institute of Japan. The ship used in this study was the S-175 container ship design with bulbous bow having the following characteristics:

Length b. p.	175 m.
Beam	25.4 m.
Draft	9.5 m.
Displacement	24,742 tonnes
Block coeff.	0.572
LCB, aft	1.42% LBP
Design Froude No.	0.275

A number of observations can be made regarding the computed results — if the two or three tanks whose results were distinctly out of line with the others are deleted — as shown in Table 1 .

Of perhaps greater significance are the comparisons made, where possible, between theory and experiment (averages, with bad results excluded):

Heave ampl.	Good agreement
Pitch ampl.	Good agreement
Roll ampl.	Poor in quartering seas (30°) Good at other headings (60, 90, 120, 150°)

Table 1

Summary of Comparison of Calculated Motions by 22 Different Model Basins for the S-175 Container Ship, Ship Research Institute of Japan (Seakeeping Committee, 1978)

	Amplitudes	Phases
Heave	— excellent	excellent
Pitch	— excellent except in the vicinity of the frequency of peak resonant response (2 groups of data)	excellent
Surge	— excellent	excellent
Roll,	with specified linear damping — good agreement when 5 sets of results were excluded	good when 5 sets of results were excluded
Roll,	with damping selected by participants — good agreement, excluding 9 sets	poor agreement excluding 6 sets
Sway	— good agreement when 6 sets of of results are excluded	good agreement when 6 sets of results are excluded
Yaw	-- fair agreement when 7 sets of results are excluded	fair agreement when 4 sets of results are excluded

Yaw ampl.	Poor agreement in quartering seas (30, 60°) Good at others (90, 120, 150°)

Dalzell (1977) has made an overall evaluation of the theory of longitudinal ship motions by rating the results of a number of authors in terms of agreement between theory and experiment for pitch, heave, relative bow motion and midship shear and bending moment in head and following seas. The accompanying Tables 2 to 5 give his results, where the index is the approximate ratio in percent between:

- Largest deviation between theory and experiment
- Largest experimental response amplitude

Values of 5-10 are considered excellent, 20 to be marginal and 30 or above to indicate problems. Dalzell cautions that discrepancies may be due to experimental inaccuracies as well as to deficiencies in theory.

Other comparisons not included are those of M. Takagi (1974), who considered roll and yaw in oblique waves as well.

TABLE 2

Approximate Measures of Correlation Between Theory and Experiment for Head Seas

Source	Fn	Pitch	Heave	Midship Vertical Moment	Midship Vertical Shear	Relative Bow Motion
Baitis, et al (1974)	.13 → .2	5-10	10-20	-	-	-
Cox and Gerzina (1975)	.22	5-10	5-15	-	-	5-10
	.30	10-15	5-15	-	-	5-30
	.37	20	10-30	-	-	5-30
Baitis and Wermter (1972)	.15	10	10	-	-	-
	.46	40	20	-	-	-
Flokstra (1974)	.22	-	10	-	-	-
	.245	10	10	10	20	10-15
	.27	-	10	-	-	-
Wahab and Vink (1975)	.15	5	-	10	15	15
	.245	15	25	15	20	25
Journee (1976)	.15	10	20	-	-	-
	.20	10	25	-	-	-
	.25	10	25	-	-	-
	.30	10	20	-	-	-
Kaplan, et al (1974)	.25-.30	10-15	-	30	20	-
Kim (1975)	.25	-	-	10	30	-
Loukakis (1975)	.15	10	10	-	-	-
	.20	15	10	-	-	-
	.25	15	10	-	-	-
	.30	15	10	-	-	-
	.09-.14	-	-	10	-	-
Salvesen, et al (1970)	.2	5	5	-	-	-
	.45	20	10	-	-	-
	.15	-	-	10	10	-
Oosterveld and van Oossanen (1975)	.3 → .4	-	-	-	-	10

Dalzell (1977)

TABLE 3

Approximate Measures of Correlation Between
Theory and Experiment for Following Seas

Source	Fn	Pitch	Heave	Midship Vertical Moment	Midship Vertical Shear
Baitis and Wermter (1972)	.15	10	15	-	-
	.46	150	80	-	-
Journee (1976)	.15	10	5	-	-
	.20	20	10	-	-
	.25	15	10	-	-
	.30	15	15	-	-
Kaplan, et al (1974)	.25 → .30	15	-	60	80
Kim (1975)	.25	-	-	25	15
Wahab and Vink (1975)	.15	5	-	25	100

TABLE 4

Approximate Measures of Correlation Between
Theory and Experiment for Bow Seas (Headings 120 to 150°)

Source	Fn	Pitch	Heave	Roll	← Midship Moments → Vertical	Lateral	Torsional	Midship Vertical Shear	C_B	GM/B
Baitis and Wermter (1972)	.15	10-15	5-10	10-50	-	-	-	-	.486	12%
	.46	30-60	10-20	25-60	-	-	-	-	.486	12%
	.15	10	10	50	-	-	-	-	.486	6%
Salvesen, et al	.15	10	-	-	15	15	20	15	.80	5
Flokstra (1974)	.245	20	30	15	15	25	40	30	.598	3.6
Fujii and Ikegami (1975)	.195	15	25	-	20	30-50	30-50	-	.6994	4.1
Kaplan, et al (1974	.25 → .30	-	-	-	40	20-40	20-90	40-90	.56	2.5
	.25 - .30	-	-	-	40	20-40	20-90	40-90	.56	5.0
Wahab and Vink (1975)	.15	10	-	-	25	20	30	30	.80	5.0
	.245	10-30	20-30	20	30-50	25	20	50-100	.598	3.6

TABLE 5

Approximate Measures of Correlation Between
Theory and Experiment for Quartering Seas (Headings 30 to 60°)

Source	Fn	Pitch	Heave	Roll	Midship Moments Vertical	Midship Moments Lateral	Midship Moments Torsional	Midship Vertical Shear	C_B	GM/B
Baitis and Wermter (1972)	.15	10	10	10	-	-	-	-	.486	12%
Salvesen, et al (1970)	.15	10	-	-	15	20	20	-	.80	5
Flokstra (1974)	.245	15	15	90	10	25	-	30	.598	3.6
Fujii and Ikegami (1975)	.195	15-20	15-20	20-35	20-25	20-80	30-40	-	.6994	4.1
Kaplan et al (1974)	.25 →.30 .25 →.30	- -	- -	90 30	50 50	30-100 20-70	10-50 40-90	60-80 60-80	.56 .56	2.5 5.0
Kim (1974)	.25	-	-	50-100	20-40	30-40	30-90	40-100	.56	2.5
Wahab and Vink (1975)	.15 .245	10 10-15	- -	- 30-40	20 20-40	50 30-50	30 50-60	100 50-100	.80 .598	5.0 3.6

A comparison of three theoretical approaches to the prediction of heave and pitch amplitudes for the "Davidson A" destroyer model was given by Beukelman (1970). See the accompanying Figure 1 which also shows two sets of experimental results. Agreement seems to be reasonably good, especially for Vugts (1970) and for Gerritsma-Beukelman (1964).

Cummins (1974) has pointed out that strip theory gives problems in the case of large bow bulbs. The so-called "large bulb phenomenon" involves not only non-linearities with wave height, particularly heave, "but also errors in estimating damping and possible errors due to three-dimensionality." Cox and Gerzina (1975) gave comparisons of experimental and theoretical results for relative bow motion and showed that the presence of a large bulb could "cause overprediction of ship wetness characteristics." Cummins concludes (1974) that, "The 'bulb phenomenon' is the only major problem found to date, but the user should take warning."

As previously noted, the non-linearity of rolling gives problems. Extensive theoretical work all over the world, especially on roll damping, was reviewed in the report of the Seakeeping Committee (1978) to the ITTC. Some researchers use a non-linear approach and others make use of linearizaation methods to obtain practically useful results.

EVALUATION AND RESEARCH NEEDS

It is of interest first to quote again from Odabasi and Hearn (1978):

"In the light of the experience gained from the application of existing strip theories and from the present demands and the future developments of the marine industry, the trends of future work on seakeeping theories can be considered to follow three interlinked directions; validation of theoretical findings, consolidation of the existing results in a form useful for the practical design process, and development of new methods (or refinement of existing methods) to find satisfactory solutions to the problems for which no satisfacotry solutions are yet available.

"Validation. In order that the theoretical predictions be confidently used in practice, comparison needs to be made between the calculated and measured results. Ideally, it would be desirable to make these comparisons by using full-scale data. The difficulty associated with such an approach lies in the collection of data, especially the wave data, although

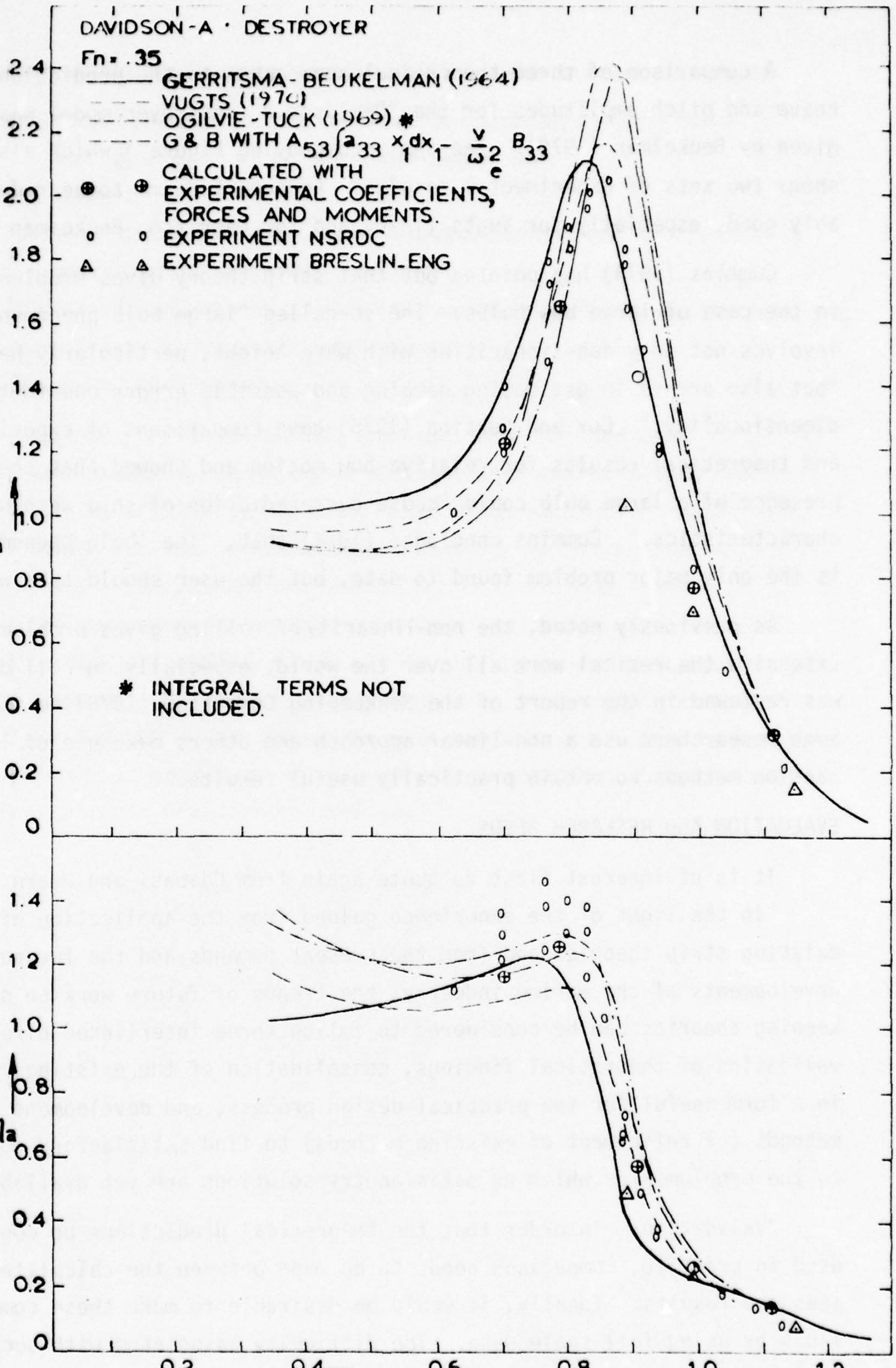

Figure 1. Comparison of Calculated and Experimental Heave and Pitch Amplitude for Davidson A Destroyer (Beukelman, 1970).

successful full-scale measurements are being gathered more frequently than before. Additionally full-scale measurements do not allow for a systematic change of the ship and the wave properties and therefore the limits of validity of existing theoretical approaches cannot be verified. A particularly viable alternative to full-scale measurements for the purpose of validation is the controlled scaled-model tests......
There is an urgent need to expand this type of experimentation to cover much broader variation of ship and wave system parameters. The quantities measured should also be extended to cover the distribution of wave exciting forces. In this respect, experimental results obtained by Moeyes (1976) indicate the necessity and importance of this type of measurement."

"Consolidation. As mentioned before, during the development of seakeeping theories the main purpose was to devise reliable prediction methods for the seakeeping analysis. In the ship design process, however, what is needed is the seakeeping synthesis, that is the direct relationship between the principal design parameters (length, beam, draught, block coefficient, weight distribution, etc.) and the seakeeping qualities. In its existing form, present computational methods are not suitable for this purpose. The designer needs simple and easy-to-use methods in the form of empirical formulae and/or graphs which will indicate to him the influence of the changes in the main design variables on the seakeeping qualities of his design, as well as providing a reasonable estimation of the quantitative values...."

"Further Research and Development. In spite of the impressive achievements during the last two decades, there are still a large number of problems which are awaiting satisfactory solutions. Recently, a recapitulation of some of these problems has been made by the appropriate committees of the 6th ISSC and 14th ITTC. Amongst these, the following may particularly be mentioned:"

- Combined action of steady and unsteady excitation
- Low frequency motions (added mass)
- Impact pressures
- Effects of square or full ends (transom stern)
- Interaction problems (more than one body)
- Large amplitude motions

Other areas for further theoretical research may be mentioned:

Non-linear effects at the surface, because above-water hull is not a reflection of the under-water body.

Roll damping

Exciting forces for short wave lengths (springing) and very long wave lengths (mooring problems).

Effects of forward motion at high speeds, especially quartering seas.

Applications to unconventional forms

Effects of shallow water

In general it can be stated, however, that the theory of ship motions has reached a stage where adequate comparisons of alternative designs can be satisfactorily made, insofar as motions in regular waves are concerned. Since, as previously noted, it is the derived responses— relative bow motion, added resistance, wave loads, etc. — that are of particular importance in evaluating seakeeping perofrmance, available techniques for calculating these will be discussed and evaluated in another chapter. In general, the possibility of selective refinement of certain aspects of the theory to meet specific practical needs should be considered in preference to excessively complicated, complete three-dimensional and/or non-linear theories.

Chapter 3

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Chapter 4
DERIVED RESPONSES

INTRODUCTION

We shall now consider the aspects of ship response to rough seas that are generally of greatest importance to the evaluation of sea-keeping performance. These are the responses that can in principle be derived from the basic five or six modes of motion. These include:

- Vertical and/or lateral motions, velocities and accelerations at specific points, i.e. local motions.
- Relative motions between a location in the ship (as the bow) and the encountered waves.
- Wave loads
- Powering in waves
- Ship control in waves

Most of these involve non-linearities, and consequently the status of our knowledge is less complete than for the basic motions.

LOCAL MOTIONS

If pitch, heave, and roll amplitudes plus phase relationships are known, it is easy to calculate vertical motions, velocities — and particularly — accelerations at any position in the ship. Furthermore, RAOs for these quantities can be used to predict statistical parameters in any irregular sea for which the spectrum is known.

Similarly, transverse motions and accelerations can be calculated by combining roll, yaw and sway amplitudes and phases. Furthermore, the combined effect of longitudinal and lateral motions can be calculated, as discussed by Hamlin (1970).

Roll angle is in itself a quantity of interest in relation to operation of some shipboard equipment and ability of personnel to move safely about the ship. However, for these considerations it is invariably the angle relative to the apparent vertical rather than to the true vertical that is of concern. The calculation of the roll relative to the apparent vertical normal to the wave slope (except in relatively short waves) requires that sway, as well as roll, be known and the phase angle between these modes of motion. The amplitudes of pure roll and

roll-with-sway may not be very different, but instantaneous values to be used for control of roll (as discussed elsewhere) may be significantly different.

RELATIVE MOTIONS

Another type of important derived response is relative vertical motion between ship and wave at various locations along the ship's length, but particularly at the bow, which can be used to predict the probability of shipping water. At first glance this appears to be almost as easy to compute as the other derived responses mentioned above, but unfortunately this is not true. Two important new factors enter in:

- The bow wave generated by the ship's forward motion raises the water level at the bow and reduces the effective freeboard; and the ship may trim somewhat underway, which will either increase or decrease the effective freeboard.
- The ship-wave interaction, which was ignored in the Froude-Kriloff hypothesis, is significant: it results in a "swell-up" of the diffraction wave caused by the ship's vertical motion, the amount of which is not obtained in the usual ship motion calculation.

The first of these effects can easily be evaluated by model tests in still water, and it can be assumed that there is linear superposition of the ship's wave and the encountered wave. The second effect is more serious, and requires both experimental and theoretical attention.

The most recent paper on shipping water by Bales (1979) reveals a scarcity of information on the above two factors — static change in water level and dynamic swell up. Regarding the first factor, Bales makes use of empirical formulas given in Bishop/Bales (1978), based on a synthesis of experimental data on destroyer-type hulls and on work of Ogilvie (1972). Journée (1976a), on the other hand, makes use of an early empirical formula of Tasaki (1963), which was found to check with measurements between stations 19-20 for a fast cargo ship model (block coeff. = 0.564). Van Sluijs (1974) gives information on static change in waterline at various stations for a frigate model with C_B = 0.449 and no bow dome. (His Fig. 24). The ship motion program of the Defence Research Establishment Atlantic (Canada) (MacKay and Schmitke, 1978) makes use of a wave profile algorithm developed from work by Shearer (1951).

As for the dynamic swell up effect, Bales (1979) makes use of data from van Sluijs (1972) and Lofft (1974), plotted in his Fig. 1 for Froude No. of 0.4, with an assumed linear variation of the factors to 1.0 at $F_N = 0$. Bales emphasizes that this information applies only to fine destroyer-type hulls without bow sonar domes, and is for head seas. The van Sluijs data extends to the stern, but Bales' figure does not. Bales found that the tendency for relative motion to be increased by dynamic effects may be reversed in following waves (1976). The ship motion program in use at the Defence Research Establishment Atlantic (Canada) (MacKay and Schmitke, 1978), makes use of van Sluijs data for dynamic swell-up.

Journée (1976) again refers to a Tasaki empirical formula ($0.60 < C_B < 0.80$) and calls attention to the assymmetry of relative motions. Tasaki's linear trend with frequency of encounter was not confirmed by Journee's experiments, but direct comparisons were not made because the model ($C_B = 0.564$) was outside the range of Tasaki's formula. Murdey (1972) compared Tasaki's formulation for the relation between dynamic swell-up and relative velocity of oscillation, which depends upon block coefficient, to measurements in waves on a model of 0.85 block coefficient. He found that although Tasaki's relation gave order-of-magnitude agreement with the measured data, there were discrepencies in short, steep waves.

Experimental trends of swell-up are given (Journée's Fig. 21) for full load and ballast conditions of the high-speed cargo ship (with bulb). It is noted that the dynamic swell-up is much greater at station 18 than at station 20. Experimental data are also given by van Sluijs and Gie (1972) for a frigate model with two different above-water bow section shapes.

In model tests of a <u>Mariner</u> hull some years ago ($C_B = 0.61$), Hoffman and Maclean (1970) found a dynamic swell up factor of 1.12 to 1.15. A recommendation was made for "further work toward establishing the statical and dynamical bow wave swell-up .... so that both can be reliably estimated." From the preceding discussion it is clear that many uncertanties remain, even for the simple head sea case. In fact, the corrections introduced in the calculations sometimes result in poorer

agreement with model test results. Lloyd, et al (1979), reporting on model tests on a "typical modern warship" without bulb, found that "The computed relative bow motion .... with no allowance made for any distortion of the waves by the ship" gave reasonably good agreement with experimental measurements at the stem of the model.

Murdey (1972) points out the lack of information on the effects of oblique headings and short-crested seas on deck wetness and recommends more experimental work. A factor present in oblique seas is that of port-to-starboard asymmetries, both those that are geometrical in nature and those associated with wave build up (weather side) and hull sheltering (leeward side).

Another important factor in bow wetness is the above-water hull form, particularly the amount of flare and the use of knuckles. The effect of bow flare has not been systematically studied, although there have been a number of limited studies. Bales neglects it entirely in his procedure (1979). One important consideration is that large amounts of flare that may be favorable to dry decks may induce pressures which can cause both local damage and high midship stresses (McCallum, 1975). Some experimental data are available, such as Newton (1960), and Bales (1978) for two aircraft carrier bow configurations. Tests in irregular waves are particularly appropriate for such studies. But theoretical work is rare, one of the best treatments being that of Kaplan (1972) dealing with flare-impact slamming. Further theoretical development is clearly needed.

One promising theoretical approach is that of Salvesen (1978), who has shown how non-linearities — such as above and below-water sectional shapes — can be accounted for without excessive complications. His second order strip theory for pitch and heave motions assumes that the ship is slender and/or that the frequency is low so that to the first order the motions are governed by hydrostatic restoring and Froude-Krilov forces. The incident wave system is represented by a second-order Stokes wave. The result is two sets of equations, one the conventional strip theory equation and the other consisting of second order terms which are products of the first-order motions and of hydrostatic restoring and Froude-Krilov forces. He states, "It is anticipated that consideration of these second-order effects will improve on the relative bow motions

computed by conventional strip theory." It is recommended that further work be pursued along these lines, along with experimental studies for verification on hulls of varying fullness and above-water form.

Relative motion at the stern may be of importance also, since some ships may be subject to "pooping" in following seas. Comparison between experiment and theory for a cargo ship hull by Journée (1976b) showed that, although calculated relative motions agreed with those determined from measured pitch, heave and wave, the measured relative motions were generally 1/3 to 1/2 as great, as a result of dynamic effects. Hence, it is clear that further work is needed on such effects in following as well as head seas.

SLAMMING

Another phenomenon related to relative bow motion is bow emergence and slamming. The prediction of bow emergence from pitch, heave and encountered wave can be expected to be reasonably reliable, since the previously mentioned effects of ship's bow wave and interaction of ship motion with encountered wave should be minimal. However, the prediction of bottom slamming and the calculation of the resulting impact pressures are complex problems that are far from satisfactory solutions. Some of the important factors, in addition to relative bow motion, at various stations:

1. Relative vertical velocity.
2. Section shape — particularly whether bottom is flat.
3. Angle between keel and wave slope at entry.
4. Extension to irregular seas.

The first item can readily be calculated from relative bow motion. The second can be described by a body plan or by a numerical measure proposed by Ochi and Motter (1973). Little or no attention has been given to the third — angle between keel and wave slope — since Tick (1958). But recent work by Beukelman (1979) has shown that at forward speed impact pressures are significantly increased if there is an angle between the bottom and the water surface. The extension to irregular waves (item 4) has been fully developed by Ochi and Motter (1969) using probability theory.

Schmitke (1979) has presented a complete computerized procedure for slamming prediction which is based primarily on Ochi and Motter (1973), but incorporates features from Stavovy and Chuang (1976), which make it applicable to fine naval hulls as well as to merchant ships — provided speed is low. The method also incorporates a number of logical improvements to make it a reasonable method considering the present state of the art. Pending further improvements in the theory, some experimental checks of the procedure would be worthwhile.

The most promising long-range theoretical approach to bottom slamming with forward speed appears to be along the lines of Beukelman (1979), bringing keel angle and wave slope into the picture.

From the point of view of hull structural design, impact on bow flare may be even more serious than bottom slamming, since the duration of the impulse is longer and the dynamic magnification factor therefore is usually greater. A number of cases of severe deck buckling as a result of flare impact were reported by McCallum (1975). Flare impact loads are discussed further in the section on Wave Loads.

On the basis of the preceding survey it is recommended that high priority be given to combined theoretical and experimental studies of engineering solutions to the non-linear problems involved in both bottom slamming and bow flare impact.

As pointed out by Tasaki, et al (1975), ". . . . extreme phenomena governing the sustained sea speed, like slamming, shipping of water and propeller racing, should be endorsed by the full-scale observations."

Meanwhile, pending the development of completely reliable theoretical methods, the value of direct experimental determination of deck wetness and slamming features of a new design should be recognized. (Murdey, 1979). Such model tests in irregular waves can be considered as analog computer solutions in which all non-linearities are automatically taken into account. Sophisticated experimental techniques (chapter 3) permit any specified sea spectrum to be reproduced in head or following seas. Expenses need not be high because large models are not required, and a single model can be fitted with a number of alternative bows or bow segments.

WAVE LOADS

Introduction

Although wave loads enter into the calculation of ship motions, they are considered here under the heading of derived responses because, in order to determine the loads at a particular instant of time, a solution to the ship motions must first be obtained.

There are three different levels at which wave loads may be needed for structure design purposes:

1. Instantaneous local hydrodynamic pressures on the surface of the hull as a result of ship motions and ships/wave interactions. These pressures may be needed over the entire hull surface or over only a portion of it.
2. Integrated instantaneous pressures yielding the bending moment and shear force at midships or other stations.
3. Impulsive pressures on local areas of the hull (flat bottom, flare, sponson, or stern) which can cause vibratory hull response (slamming, whipping, springing).

Local Pressures

The introduction of finite element structural analysis techniques has given impetus to the development of methods of calculating the distribution of instantaneous hydrodynamic pressures over individual sections and hence over the entire surface of a hull oscillating in waves. Quoting from Hoffman (1975), who gives an excellent survey of the problem, "Havelock (1940) was the first to work out the simplified problem of determining the average steady pressure on a fixed cylinder of infinite draft due to the wave motion. Abels (1959) computed the pressure distribution for a fixed ship model in waves. The pressure due to body motions was excluded from both works. In 1960's Porter (1962), Paulling and Richardson (1965) and Hou-Wen Huang (1965) made a series of theoretical calculations and experimental measurements of the hydrodynamic pressure on the two-dimensional cylinders of a ship-like cross section oscillating vertically on the free surface.

"Hoffman (1966) and Tasai (1966) simultaneously, but separately, published papers showing the methods to compute the wave-induced pressure

on the hull surface of a ship heaving and pitching in regular longitudinal waves. Hoffman also measured the pressure distribution on a T-2 tanker model, and found that the experimental results had good agreement with theoretical calculations. Goda (1967) carried out similar theoretical calculation and experimental work. He also used a T-2 tanker model to compare theory and experiment.

"Some extensive work including calculations and experiments has been done later by Goda et al (1973) on the ore carrier Kasagisan Maru model, the results showing quite good agreement for both motions and pressures. Tasai (1968a) also developed a method for calculating the hydrodynamic pressure distribution along the contour of a transverse section in beam seas. More recent evaluation of hydrodynamic pressure acting over the hull of a ship in waves, based on Tasai's method, accounting for all degrees of freedom of motions, has been worked out by Fukuda et al (1973). Full-scale measurements of motions, pressures and stresses on a 35,000 ton deadweight container ship Nihon have been carried out recently by Taylor and Lundgren (1975) to ascertain the reliability of analytical methods for loadings in waves by the strip theory."

For a detailed finite element analysis, therefore, we have a tool for obtaining the distribution of pressures around one or more sections at any instant in the cycle of ship response to any assumed regular wave. From the known distribution of weights and the calculated ship motions the local gravity and inertial reaction forces can also be computed for input into the structural analysis.

A recent paper by Jan, et al (1979) reports a study carried out by ABS for the SSC in which finite element stress calculations for the SL-7 container ships were compared with stresses measured both in calm water and at sea, using the best available wave data. "The overall comparison between calculated and measured stresses for the dockside calibration is good where thermal effects were small .... and the comparison of instantaneous stresses in head seas and in oblique seas is also good for the wave conditions considered." These results are encouraging, although it must be noted that there were many uncertainties involved in the calculations.

Although a tool is available for calculating hull surface pressures, as noted above, further checking of the hydrodynamic theory is necessary. In addition, clarification is needed of the local pressure distribution around a section between the still water level and a wave crest, as well as the modified distribution just below a wave hollow.

Hull Bending Loads*

The study of non-vibratory wave-induced response of the hull girder began with a pioneering project sponsored by the Hull Structure Committee, SNAME, at the Davidson Laboratory and reported by Lewis (1954). A model of a T-2 tanker, jointed amidships, was subjected to head and following seas and the fluctuating bending moment measured. (First mode vibration of the jointed hull was also identified and recorded.) Since this experimental work preceded any known analytical treatment of the subject, it was with some surprise that the experimenters noted a reduction in bending moment from the values calculated by conventional quasi-static methods. (This reduction was later found to have been exaggerated at certain speeds because of dynamic effects in the moment measurements, Lewis (1958)).

The analytical treatment of ship motions and wave loads by Korvin-Kroukovsky (1957) and his associates followed quickly. The bending moment was shown to be the result of integrating hydrodynamic and inertia (D'Alembert) forces over the ship length (Jacobs, 1958). The work explained the reduction in dynamic wave bending moments on the basis of two factors: the well-known "Smith effect", which accounts for the pressure reduction in a wave crest and increase in a trough resulting from the orbital motion of wave particles, and a second effect of comparable magnitude resulting from ship-wave interaction (damping and added mass).

Further research has established that pitching motion, per se, has a relatively small effect on wave bending moments. But heaving is of greater significance, as shown for example in the photograph published as Fig. 25 of Lewis (1954). Here the model is shown in sagging condition with the load waterline completely out of the water over the entire length of the ship. (Static buoyancy is clearly less than half normal displacement.)

Further experimental work established that the wave induced bending moment is not basically a resonance phenomenon. For example, experiments

*The remainder of this section on Wave Loads is based on Lewis (1974).

by Dalzell (1962) showed that when data for a wide range of model speeds are plotted on the basis of wave length they collapse into a fairly narrow band, as indicated by Fig. 2 . In other words, the geometrical relationship between wave and ship—or "ship/wave matching" (Bishop, et al, 1973) — is of prime significance.

Similar RAOs were given by Birmingham (1971) for naval ships, although he mistakenly refers to them as "resonance curves."

However, the simple concept of wave-matching is not the whole story. for Moor (1967) has shown that the curve of bending moment vs. wave length will in general have a double peak. This finding was confirmed by strip theory calculations, and formulas were given for estimating the position and magnitude of the two peaks. In discussing the paper Fukuda confirmed the existence of two peaks and reported that the peaks were more prominent when the static moments of weight in the fore and after bodies about midships were relatively small. Jensen/Pedersen (1978).

Various experimenters (Løtveit, et al 1961; Vedeler and Løtveit, 1961) have confirmed the sensitivity of bending moment to weight distribution and have explained it on the basis of a direct effect, the distribution of inertia forces, and an indirect effect resulting from changes in the pitching and heaving motions. Swaan and Joosen (1965) had previously noted that the bending moment was more dependent on the moments of weight about midships than on the radius of gyration, per se. Murdey (1968) carried out further tests with variation in weight distribution without change in the radius of gyration. He confirmed that "a reduction in the moments of weight in each half of the model increases the maximum measured wave bending moment and accentuates a theoretically expected double peak effect". By theoretical calculations he showed how the inertial and hydrodynamic bending moments can be separately calculated and that the double peaks depend on how the two components combine with one another.

Murdey's separation of inertia and hydrodynamic moments is also interesting because it shows that separately these effects are very large, especially at wave length/ship length ratios of 1.2 to 2.0. The net wave-induced bending moment is simply the difference between these two

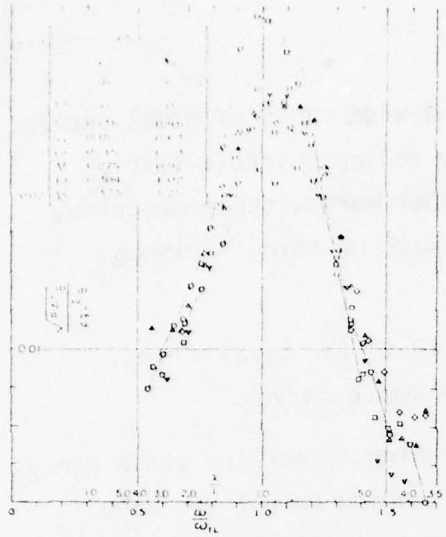
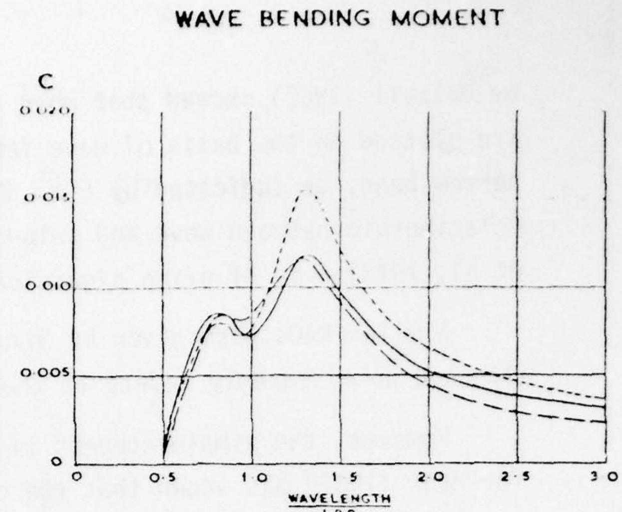


Figure 2. Destroyer Bending Moment Amplitude Response in Head Seas vs Wave Length (Dalzell, 1962).



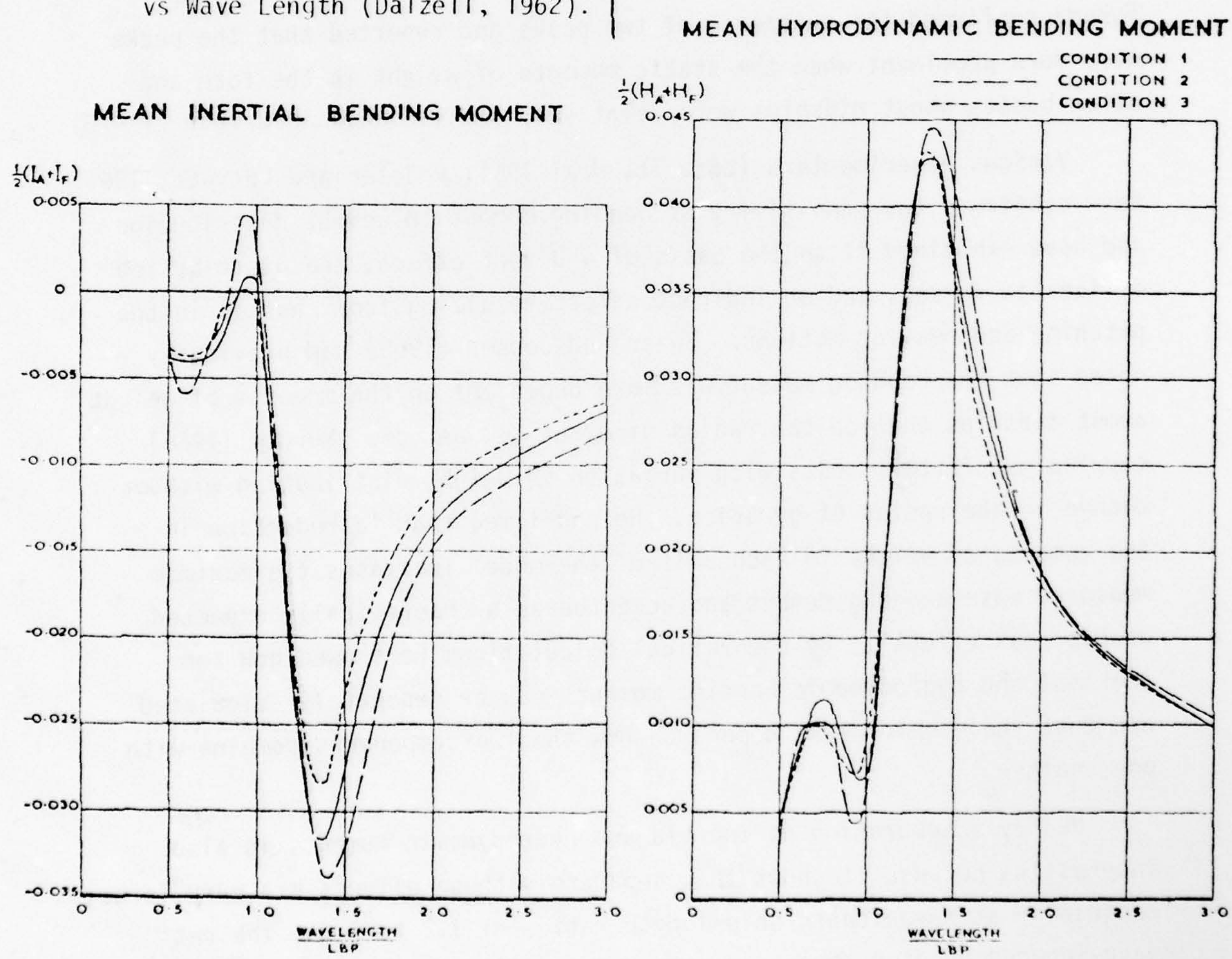


Figure 3. Bending Moment Coefficient for a Small Cargo Ship (Wave Crest Amidships) (Murdey, 1968).

large quantities. For example, in the case cited the peak hydrodynamic moment coefficient (hogging) was 0.043 at $L_w/L = 1.4$, the inertial moment coefficient was - 0.031, and the difference was 0.012, as illustrated in Fig. 3 .

Other research, both theoretical and experimental, has been extended to include lateral bending and torsion in oblique seas (Dalzell and Chiocco, 1973). Excellent agreement has been obtained generally between theory and model tests, as shown, for example, in the tabulations prepared by Dalzell (1977) and quoted in the chapter on Ship Motions. However, a significant exception will be noted in the case of high-speed ships in quartering and following seas, as for example the results of Kaplan, et al (1974), where encountered frequencies approach zero and rolling is a factor.

A detailed study was made by Kaplan, et al (1977) of possible deficiencies in the theory (Kaplan, et al, 1974) and sources of possible errors in the experiments (Dalzell, et al, 1973), "As a result of this investigation a number of conclusions have been obtained. The different elements considered to modify the basic theory have been shown to have negligible effect, except for the addition of certain speed-dependent terms in the equations of motion that result in the extended SCORES theory. This theoretical model has shown good correlation with model test data for conventional ships, another large fast container ship similar to SL-7, and also for the SL-7 vertical plane responses. The extended SCORES theory can be used over the entire range of conditions, with sufficient accuracy at low encounter frequencies, and does not require special treatment of hydrodynamic forces just for that region in order to provide adequate vertical plane load predictions.

"The major problem for correlation of the SL-7 lateral plane responses occurs in quartering-sea conditions where large roll motion occurs. While the problem of proper roll motion prediction generally exists in this case as well as for other ships, there appear to be problems in the model experiments and determination of model characteristics related to roll that raise questions as to the validity of the present SL-7 model test data for these operating conditions. This is considered to be due to inconsistent values of roll static and inertial properties, lack of

repeatable test results due to the model directional control behavior, etc.

"At this time it appears that the use of computer calculations for load prediction of ships, including the SL-7 type of container ship, is a suitable tool for further use as long as adequate input data on the ship characteristics is provided. The benefits of calculation methods in regard to time and cost factors are evident, and the overall agreement between theory and experiment has had sufficient verification to allow its utility for this purpose.

"The present study points out a number of recommendations for further work in this area of SL-7 data correlation, which are listed below:

1. Further model tests should be carried out in the quartering-sea range, preferably with a larger model and/or special test apparatus that would be more suitable to such tender ship models with directional control problems.

2. A more detailed determination should be made of the model roll static and inertial properties prior to the tests to insure consistency of the resulting values.

3. The roll decay tests should be made with more information on time histories of motion presented, thereby allowing more precise analysis to evaluate damping parameters (linear and nonlinear), as well as using more than one method of initial roll disturbance as a means of checking repeatability of decay characteristics.

4. The correlation analysis associated with the data obtained from the tests described above can be carried out using the present extended SCORES theory, with input data pertinent to the model that is being re-tested. Such a comparison will provide a more definitive answer concerning the relation of theory and model tests for predictive purposes when considering lateral plane responses in quartering seas."

The principle of superposition has been applied to the prediction of bending moments in irregular short-crested seas, as defined by their directional spectra. This procedure yields short-term statistics which can be integrated over sea condition to obtain long-term predictions (Lewis, et al, 1973).

Full-scale statistical data on wave bending moments have been collected over periods of 2 to 3 years in the form of stresses or strains. Fortunately, it has been found that a ship's hull, even though a built-up box girder rather than a homogeneous beam, follows the simple beam theory quite well, provided that areas of stress concentration are specially considered. Consequently, measured stresses can be interpreted as external bending moments, with the help of simple dockside "calibrations". Probability theory has been applied to the extrapolation of such data to obtain long-term cumulative distributions of bending moment (Hoffman, et al, 1972; Little, et al, 1971).

Results of a careful series of short-term comparisons between calculations and full-scale, including buoy wave measurements, were presented by Taylor and Lundgren (1975) for the tanker Nihon. Quoting from the report of Committee I.2, Loads Introduced by Wind, Waves and Motions," to the ISSC (1976),

"The results of the investigation indicate that the theoretical methods used predict the full-scale response behavior satisfactorily, particularly the ship motions. The structural responses are, however, highly affected by the component of vertical bending which appears to be considerably overestimated in the theoretical calculations, especially in stern and quartering seas. The calculated pressures were in good agreement with those measured. It can also be seen that the horizontal bending stress and the torsional (warping) stress were also predicted quite well by theory."

In recent years considerable effort has been expanded on the development of methods of predicting long-term bending moment trends for commercial ships from calculated or model test RAOs and families of representative ocean wave spectra (Nordenstrøm 1969; Lewis 1967, 1974; ISSC, 1976, etc.) Results have been used by classification societies as guidance for developing strength standards for ever larger tankers and for Great Lakes bulk carriers (Stiansen, 1975, 1977). Further development is dependent on a better understanding of hull strength in statistical terms.

Although Roop (1932) made a limited statistical approach to the problem of longitudinal strength many years ago, little work along this line was done on naval ships until an investigation of destroyer-type

hulls by Zubaly and Compton (1965). A probabilistic study was made by Birmingham (1971), in which he derived bending moment RAOs for 7 ships from trials in which wave records were made by means of shipborne recorders. He calculated short-term bending moments for wave spectra representing different sea states and then predicted "lifetime loads" for 14 years' operation in the North Atlantic on the basis of a number of assumptions regarding effects of ship heading, speed, wave spectra, etc. The approach was sound, but some refinement and extension would be desirable.

Buckley (1978) has investigated the problem of obtaining realistic wave loads for ship design, with particular emphasis on the study of data on unusually severe sea conditions and on actual cases of structural damage to ships in storms. In this report the cases of damage cited were commercial vessels, but he suggests that similar data for naval ships be obtained. Further work is needed from the viewpoint of weight saving.

Impulsive Loads

The vibratory modes of hull girder response can be considered to be subdivided on the basis of the nature of the excitation into transient and cyclic, or steady-state. The former category is generally described by the terms slamming and whipping, where slamming refers to the initial effect of a wave-ship impact and whipping to the consequent hull vibration in one or more modes. Cyclic responses can be self-excited, as by ship's machinery or propellers, or externally excited by encountered waves. The latter is of particular interest here and is generally referred to as springing.

Both the transient and cyclic hull responses can in principle be handled by the theory of vibration of a free-free beam. However, there are more difficulties here than in the case of quasi-static loadings. First of all, the dynamic response of a ship hull does not follow simple beam theory. In the case of a typical cargo ship with double bottom it has been hypothesized (Kline and Clough, 1967) that it can be described as a composite beam consisting of the double bottom, having certain elastic properties, and the superimposed hull having other properties. A second problem is the cargo and other loads carried by the ship which in many cases appear to act as sprung masses whose properties are difficult to compute. Third is the problem of damping, which is twofold: internal,

involving the structure and the cargo loads, and external, involving mainly hydrodynamic effects. Both are difficult to calculate, but they can be determined experimentally on full-scale ships, combined, by anchor-drop or shaker tests. Hydrodynamic effects are troublesome to evaluate separately.

The state of the art for the determination of slam loads on the hull girder is well summarized in the Report of Committee 8 to the ISSC (1973). There it is noted that there is reasonable agreement between two-dimensional drop tests and theory, when theory includes the effect of entrapped air and water surface deformation. However, pressures obtained in two-dimensional experiments are consistently higher than those obtained in ship model tests. The difference is believed to be due to the effect of surface waves, as well as the angle of impact of the bottom on the water surface. Scale effect problems in experimental work are discussed by Sellars (1971).

In spite of the above difficulties, two approximate methods of calculating pressures are now available, one by Ochi and Motter (1973) for merchant hull form and the other by Stavovy and Chuang (1976) for high-speed vehicles. The former assumes that the local pressure at a critical section is the product of the square of the relative vertical velocity and a form factor dependent on section shape. Form factors are derived empirically from model tests and full-scale data, using Froude scaling. No account is taken of angle between keel and wave slope nor of differences in ship speed. The second method is applicable to V-shaped forms without significant flat of bottom and takes account of the angle between keel and wave slope. Because of the latter refinement, this method is more difficult to incorporate into conventional ship motion calculations, but it has considerable promise for the future.

A recent study by Beukelman (1979) gives results of some interesting forced oscillation tests (pitch and heave in calm water) on a Series 60, 0.70 block, model. Among the findings, "the bottom impact pressure in cases where there is forward speed appeared to be much higher if there is an angle between the bottom and water surface at the moment of impact." A theoretical development in the paper accounts for this on the basis of a term involving the product of sectional added mass x vertical acceleration, where the latter includes a component resulting from forward velocity.

In general, agreement between the theory and the experimental results was satisfactory. Comparisons were also made between the experimental data and these theoretical methods:

I. Takezawa (1975), Chuang (1966), Verhagen (1967)

II. M. D. Ochi (1970), Ochi and Motter (1973)

III. Stavovy and Chuang (1976), Kaplan and Malakhoff (1978)

It was found that for flat impact the first group of methods gave a good estimate of peak pressure, while the second group gave lower values. But where there was an angle between bottom and water surface all of these methods gave results that were too low. On the other hand, the group III methods produced values which were too high — although Stavovy and Chuang (1976) gave better agreement. Results by the method of the paper gave the best agreement with experiment.

Thus, it appears that theory is making good progress toward a solution to the problem of calculating bottom slamming pressures, including the effects of forward speed.

Since the relative velocity can be assumed to follow the Rayleigh probability law, the distribution function for bottom pressure at a particular heading and speed can be calculated for each sea condition considered, and hence the most probable extreme value in a stated period of time (as the average duration of a storm) can be determined for each.

Next it is necessary to estimate the time and space distribution of pressure over the bottom. Ochi has done this on the basis of a series of assumptions that seem reasonable but have not been completely verified. The time and space-varying pressure determined from the above can be integrated to provide the input to a calculation of structural response as shown in Fig. 4 . The transient loading associated with flare

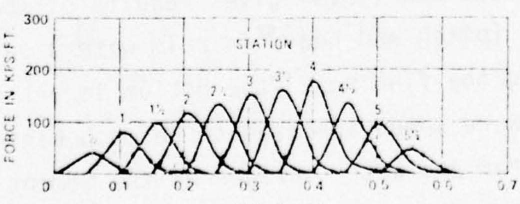


Figure 4. Calculated Impact Forces at Various Stations as a Function of Time; Mariner Cargo Ship (Ochi, 1973)

immersion is characterized by a longer duration of impact than bottom slamming. As previously noted, elementary beam theory shows that the dynamic load factor will therefore in general be greater. For example, consider the case of a 500-ft cargo ship with natural period of vibration, T, of 0.75 s. Assume that the duration of a bottom slam impact, t_1 is 0.1 s and of a flare immersion impact is 0·5 s. Then in the first case $t_1/T = 0.13$ and in the second $t_1/T = 0.67$. Simple theory (Frankland, 1942) assuming triangular or sinusoidal pulses gives a magnification factor of 0·3 in the first case and 1.5 in the second. Deck buckling resulting from flare impact is reported by McCallum (1975).

A theoretical treatment of the important case of flare immersion has been given by Kaplan and his associates (1972). The applied load is computed on the basis of the "non-linear variations in buoyancy and inertial forces, over and above those used in the linear ship motion analysis". Results are obtained as time domain solutions of structural response to various wave inputs, as well as r.m.s. values and other statistical properties. Work has also been done by Kumai and Tasai (1970).

A proposed project of the Ship Structure Committee for FY 1980 is to develop a computer model for predicting motions and loads taking account of hull shape <u>above</u> the waterline. See also Suhara (1976) and Murdey (1972).

For naval ships impact on above-water appendages is a problem. Keane (1978) has pointed out that, "no analytic methods exist for assessing the hydrodynamic loads imposed upon sponsons at various heights above the waterline during the early stages of design." This has resulted in serious design delays while time-consuming model studies were carried out.

Another dynamic effect is that of local wave "slap" or impact of short waves. Fujii and Takahashi (1972) have described this for the case of large, full ships.

Another source of transient loading that excites vibratory response is the shipping of water on deck forward. In many cases this load may simply be the static head of the water scooped up by the bow acting downward until it runs off. The duration of this load therefore is relatively long, more like flare immersion than a bottom slam.

However, there may be a dynamic component, especially if the ship is moving forward at high speed into head seas. The water in the wave crest will be moving in a direction opposite to the ship and therefore its velocity is additive to that of the ship. Since the bow will normally be pitched downward at the time of shipping water, a sizable dynamic force downward can result. Experimental values of pressures have been reported by Tasai (1968b, 1971).

Shipping water can be predicted on the basis of the same calculations of relative bow motion discussed in connection with slamming. The only condition is this case, however, is that relative motion exceed the bow freeboard. Such predictions have proved reasonably satisfactory, but are subject to error from the bow wave due to forward speed and from non-linear effects (Hoffman and Maclean, 1970; Fukuda, et al, 1970; Tazaki, 1960). See preceding section on Relative Motions.

The whipping that results from shipping water is more significant than the relatively small increase in hogging moment. It has been calculated and compared with model test results (Ochi, 1964; Kawakami, 1969). It has also been recorded full-scale by Aertssen (1969). Ferdinande (1969) discusses a case in which whipping was induced by the emergence of the bulbous bow of an ore carrier.

Springing

As mentioned in the Introduction, one type of steady-state dynamic effect is known as "springing". This phenomenon has been noticed particularly in Great Lakes bulk carriers (Matthews, 1967), but it has also been reported on large ocean-going ships of full form (Goodman, 1971). A clue to the origin is given by the fact that the Great Lakes bulk carriers are quite shallow in depth and consequently have unusually long natural periods of vertical hull vibration (two-noded periods of 2s or longer). The explanation is that when the ship is running into comparatively short waves that give resonance with the natural period of vibration, significant vibration is produced. This vibratory response may continue over some period of time, gradually fluctuating in magnitude. A corresponding fluctuation in stress amidships is therefore superimposed on the quasi-static wave bending stress. The springing stress appears to have the characteristics of a stochastic process, one

that may be almost independent of the low-frequency wave bending, which — as previously noted — is also treated as a stochastic process (Miles, 1971; Lewis and Wheaton, 1971).

Kumai has shown (1972, 1973) that springing can also be caused by harmonics of the long-wave excitations that produce quasi-static bending moments.

The well-developed strip theory of ship motions has been applied to springing in short waves (Goodman, 1971). Although motions of a springing ship may then be very small, the theory provides information on the exciting forces acting on the ship in the short waves that produce springing. Hence, when these forces are applied to the ship as a simple beam the vibratory response can be predicted. Despite the fact that strip theory is not rigorously applicable to such short waves, results for one ocean-going ship were found to agree quite well with full-scale records. Further coordination between theory and experiment has been attempted for Great Lakes ships, including model tests where idealized wave conditions can be provided (Hoffman and van Hooff, 1973, 1974). To investigate the influence of the wave length ratio Wereldsma and Moeyes (1976) carried out vertical wave load measurements on a model of a large tanker divided in 24 sections. The wave length ratios varied from 0.065 to 1.5. They concluded that the strip theory gives satisfactory predictions of the wave load distribution along the length of the ship for wavelengths longer than half the ship length. For smaller wave lengths, which are important for springing phenomena, the strip theory breaks down. Careful study of the results shows, however, that the principal discrepencies are along the ship's parallel middle body. The loads at bow and stern, which make the principal contributions to the springing excitation, are reasonably well predicted.

The principal deficiency in the present calculation technique is in the determination of hydrodynamic damping, particularly as influenced by forward speed. Hoffman and van Hooff (1974) showed an unexplained increase in damping on a jointed model running at increasing speeds in calm water. Once a physical explanation of this phenomenon is established, the effect can no doubt be calculated or estimated.

In irregular seas there may be sufficient energy present in the short, high-frequency waves to excite springing even in moderately rough seas. However, recent work at Webb Institute of Naval Architecture under A.B.S. sponsorship has confirmed that springing can be excited by the longer wave components of the spectrum. This apparently non-linear phenomenon requires further investigation. (Kumai, 1972, 1973).

When the calculation procedures have been tested and revised as necessary, a tool will be available for predicting springing stresses in a new ship design.

Needed Research

This survey has shown that a great deal is known about the wave-induced loads on ship hulls and their response thereto. The urgent problems are in general to make refinements of theory rather than to overcome fundamental difficulties. It may be a matter of personal bias, but this author believes that the more serious problems lie in the areas of structural response rather than of loads.

Some load problems:

- Verification and refinement of techniques for calculating hull surface pressures.
- Effect of speed on hull bending loads in quartering and following seas.
- Trends of long-term bending moments on naval vessels (using probability theory).
- More accurate calculation of slam impact pressures from ship and sea characteristics, including pressure-velocity relationships for the three-dimensional hull.
- Concise method of calculating distribution of slam pressures in space and time, with full-scale verification.
- Hydrodynamic damping, especially as influenced by ship forward speed.
- Flare entry impact loads.
- Phase relationships between dynamic and quasi-static hull loads.
- Refinement and verification of springing theory.

POWERING IN WAVES

The capability for estimation of power requirements in rough seas is important both for the design of the ship and for its efficient operation. (See chapter on Applications). There are two basic approaches that have been used, both involving model testing, either directly or indirectly:

1) Determination of added resistance, estimation of propulsion factors and hence calculations of SHP and RPM.
2) Direct self-propelled testing in waves — either in irregular waves, or in regular waves with calculation for irregular waves by superposition.

The many uncertainties involved in the first method have led to a general prefer nce for the second method. Consequently the following recommendation was adopted by the 13th ITTC in 1972:

"The Conference recommends that the following procedure agreed between the Seakeeping and Performance Committees be adopted as an interim standard, for the prediction of power increase in head waves, for normal ship types at moderate Froude numbers. It is intended that this procedure be adopted by those tanks using regular waves. If irregular waves are used, the mean power increase in particular spectra may be derived from the direct measurement of propeller torque and revolutions:

1. Experiments should be carried out with the model self propelled at model self propulsion point in regular head waves and in calm water as detailed in the 1969 Standards for Seakeeping Experiments in Head and Following Seas, 12th ITTC. Propeller rate of rotation should be maintained constant during each experiment.
2. Measurements should be made of the mean torque, $Q(\omega)$ and of propeller rate of rotation, $n(\omega)$, for each experiment.
3. The power increase, P_{AW}, in irregular waves with spectrum $S(\omega)$ should be calculated using the formula:

$$P_{AW} = 16 \pi \int_0^\infty \frac{1}{\zeta_W^2} \left[n(\omega) Q(\omega) - n_{SW} Q_{SW} \right] S(\omega) \, d\omega$$

where Q_{SW} and n_{SW} are the values of propeller torque and rate of rotation measured in still water at the time of the experiments in waves, and ζ_w is the waveheight at which the experiments in regular waves were carried out. The spectrum should be selected according to the recommendations of the 12th ITTC."

At the 14th ITTC in 1975 a survey revealed that, "while the technical merits of the standard method are not in question, it appears that the procedure agreed in principle at last Conference is not being accepted as a standard in practice." Hence, the following new recommendation was adopted:

"Efforts should continue to be made to gain experience with the interim standard for the prediction of power increase in head waves for normal ship types at moderate Froude numbers. The review of all methods of predicting power increase due to waves should be continued."

The report of the Seakeeping Committee (1978) to the 15th ITTC discusses the relative merits of direct power measurements in waves and the so-called thrust method, which uses thrust increase measured on a self-propelled model in waves together with propulsion factors from overload tests in calm water. No conclusion could be reached other than a recommendation that work be continued.

A recent survey of alternative test methods was given by Day, Reed, and Lin (1977) along with a description of the technique now in use at DTNSRDC. The latter involves the self-propelled testing of one model both in calm water and in regular waves of various lengths at model self-propulsion point. Added power in waves is then determined by Murdey's Direct Power Method, which is essentially the same as the 13th ITTC method.

"Given model torque (Q) and propeller speed data (n), the added power in a wave of amplitude ζ_a is given as:

$$P_D\ (\omega) = \frac{2\pi}{550}\ [Q + \delta\ Q(\omega)]\ [n + n(\omega)] - Q\ n,$$

where $\delta\ Q(\omega)$ and $\delta h\ (\omega)$ are the added torque and added propeller revolutions at the given wave frequency ω. The mean added power in a sea spectrum is:

$$\Delta P_D = 2\, S(\omega)\, \frac{\Delta P(\omega)}{\zeta_a^2(\omega)}\, \delta\, (\omega)$$

where $S(\omega)$ is the model - scale wave spectrum."

Nevertheless, in the long run a reliable calculation procedure must be the ultimate goal. Hence, attention must be given both to the best method to give immediately useful answers and work directed at the following aspects of the problem by both experimental and theoretical methods:

Added wave resistance
Wind resistance
Propulsion factors
Power plant factors

Added Resistance in Waves

Considering added resistance in waves, the following summary is quoted from Odabasi and Hearn (1977-78):

"The first known attempt to calculate the steady forces acting on a ship under the action of waves is due to Kreitner (1939) who attributed these forces to the reflection of waves. Havelock (1937) considered only the longitudinal component of this steady force, i.e. resistance increase, and by using the Froude-Krylov theory he related the resistance increase to the phase differences between the ship and the wave motions for pitching and heaving. Maruo (1957, 1960) used the conservation of energy principle to formulate the steady force problems and later proposed simplified methods for their numerical calculation." Others contributing to the subject have been Vossers (1961), Joosen (1966), Newman (1967), Lee and Newman (1971), Salvesen (1974), Lin and Reed (1976), Dalzell and Kim (1976), and Ankudinov (1972). A comparatively simple theoretical approach by Gerritsma and Beukelman (1972) considered the added resistance to be the result of the damping waves radiated from the ship's hull. The method was simpler to use than other methods and showed good agreement with experiments.

A design-oriented survey paper by Strom-Tejsen, et al (1973) compared calculations by three different methods — Maruo, Joosen, and Gerritsma/Beukelman — with experimental results in head seas for destroyer and

Series 60 (0.60 to 0.80 block coefficient) models. Although until recently the most generally used method was that of Maruo (1957), these experiments showed that this approach is not applicable to bulbous bow and transom stern forms. It was concluded that, "in general, the technique presented by Gerritsma and Beukelman (1972) appears to produce the most consistent and accurate mean added resistance response curves of the three methods studied. Although the correspondence between this theory and the experimentally determined added resistance is not exact, experience with these and several other ship forms has indicated that the Gerritsma-Beukelman method is the most reliable technique available for computing mean response curves."

The ITTC '78 Seakeeping Report states, "Professor Maruo, in a written contribution to the Committee, explains that the original formulae in Maruo (1963) may be simplified if frequency of encounter is sufficiently large. The revised formula is similar to that of Gerritsma, et al (1972), but there is a slight deviation in the term giving the effect of forward speed. Professor Maruo found good agreement between experiment and the simplified theory for Series 60 models." Thus it appears that the differences between these two approaches has been narrowed. Nevertheless, the comparisons of Strom - Tejsen, et al (1973) showed that the Gerritsma/Beukelman method was not satisfactory in all cases, particularly for fine cruiser-stern type hulls (Series 60, C_B = 0.60 and 0.65).

Recently Salvesen (1978) has presented a new theory in which second-order effects are expressed as a product of first-order terms that are all computed by programs presently in use for predicting linear heave and pitch motions. Furthermore, the theory applied to oblique waves as well as head seas. Hence, the mean added resistance in short-crested seas can be obtained from the regular-wave results. Comparisons were made between theory and experiment in head seas for Series 60 hulls (C_B = 0.60, 0.70, 0.80) for a destroyer at F_N = 0.25 and 0.35 and for a high-speed, bulbous-bow form at F_N = 0.20 - 0.50. In a few cases the new theory was not quite as good as Gerritsma/Beukelman (destroyer hull at low speed), but in other cases it was much better (fine Series 60 models). (All calculations by Gerritsma/Beukelman were based on motion calculations by the method of Salvesen, et al (1970)).

A comparison by Journée (1976) of model tests on a cargo ship in following seas with strip theory calculations showed considerable discrepencies. Experiments (with surge restraint) indicated generally small positive added resistances, while theory gave negative values except in very short waves.

Meanwhile, Jinkine and Ferdinade (1974) have presented an empirical method of calculating added resistance, applicable to fine ships with C_b between 0.56 and 0.65. It is based on the analysis of model test results on four ships by different experiments. This approach might be pursued further.

An important consideration — especially for ship operation — is power and speed at oblique headings to waves, since it is often desirable to compare a change of course with a speed reduction. Some experimental work along this line has been done recently, as for example a study by Fujii and Takahashi (1975) on resistance increase in oblique seas. Such oblique wave tests require rather complex instrumentation, as discussed in the Proceedings of ITTC '78. The added resistance — as well as the sideways drift force—is derived theoretically by N. Salvesen (1974) (1978), as well as by Maruo (1963).

In the case of very full ships, the effect of wave reflection may become serious — both for head and oblique seas. A formula based on Havelock's equation for drifting force on a vertical cylinder is given by Fujii and Takahashi (1975). It was found to check fairly well in comparison with tanker model tests in head seas.

Hence, it is concluded that a good, practical engineering tool is available for approximating added resistance in head seas and that this can be significantly improved by refinements in the theory without departing from strip theory or linear ship motion responses. Further work is needed to clarify the situation in oblique and following seas, however.

Wind Resistance

Although wind is not responsible for a large increase in resistance, even for high-speed ships, it should be included in a computer evaluation of added resistance and power. Data are available for making estimates

that are accurate enough for most purposes, such as van Berlekom, et al (1975) and Isherwood (1973).

Propulsion Factors

Of course, the prediction of ship power in waves from resistance data requires knowledge of propulsion factors in waves. Gerritsma (1976) states that, "Experiments by Goeman (1974), who used a forced oscillating ship model with a propeller running at constant speed, have shown that the influence of frequency of motion on the thrust and power is very small and can be neglected for practical purposes, when the propeller does not suffer from air suction. Thus for the sustained seaspeed calculation only the decrease of efficiency due to the higher loading is of interest, provided that extreme conditions are excluded."

However, Murdey (1979) says, "It is usually assumed that these are the same as in calm water with the propeller loading the same as the average loading in waves. Although this assumption has been used satisfactorily to provide engineering solutions (Journée, 1976), there is evidence (Nakamura and Naito, 1977) that the propulsion factors in waves are not the same as in calm water. These differences are most marked for models of ships tested at ballast drafts." More study of propulsion factors is clearly needed.

Power Plant

An important feature of the 1978 ITTC report was its recognition of the distinction between power increase and involuntary speed reduction. The power — and hence speed — attainable depends on the characteristics of the power plant as well as the influence of waves on added power. A steam turbine will tend to develop constant power at constant throttle, even though RPM are reduced by heavy weather; a diesel engine will tend to develop constant torque and hence reduced power in heavy weather. For practical purposes these considerations must be given attention, and if a complete speed/power curve is determined for each sea condition (and heading) it is necessary simply to use the correct SHP in reading off maximum attainable speed.

An alternative approach is to measure the speed of the model when run at maximum power, considering the characteristics of the power plant. Experimental work along this line was described by Nakamura and Fujii

(1977). A speed control was built which enables the engine characteristics to be simulated during model tests, i.e. constant RPM, constant torque or constant power. Results are presented of tests on a container ship model in regular and irregular head seas in which speed reduction was determined under either constant torque (decreasing power) or constant RPM (increasing power). This experimental approach is recommended as the most direct way to evaluate attainable sea speed under different sea conditions.

Needed Research

The preceding survey has shown the need for further development and standardization of experimental methods for determining added power requirements in waves.

Development and verification of theoretical methods to determine added resistance in oblique waves is needed, and to clarify the situation in following seas.

Further work on propulsion factors at all headings to waves is needed as an important aspect of the prediction of power requirements at sea.

The ultimate need is for a complete method of calculating for a new design SHP curves for various sea states and ship headings, as given by Aertssen (1972) from ship voyage data.

SHIP CONTROL IN WAVES

Introduction

Requirements for executing turns and other maneuvers in rough seas seldom apply to merchant ships but may be important for naval vessels. However, no specific statements regarding desirable maneuvering capabilities or actual performance have been found — other than required tactical diameter or distance for a course change (overshoot maneuver) in calm water (Keane, 1978). A paper by the Controllability Panel (H10) (1975) considers ship controllability requirements and capabilities primarily from the viewpoint of maneuvering in restricted waters. They conclude, "Few indices of controllability in use today relate to real controllability requirements," and "The development of realistic controllability indices deserves highest priority."

On the other hand, steering — maintaining a desired course or heading in any and all sea conditions — is of acknowledged importance to ships of all types. One reason for this is the need to minimize rough-sea power requirements and fuel consumption. On the one hand, excessive rudder activity adds directly to resistance. On the other hand, an erratic ship's path increases ship resistance and power expenditure. The ideal is a directionally stable hull with a control system that provides an optimum combination of good course-keeping and moderate rudder activity. Most of the technical knowledge is available — except for the problem of optimizing course keeping and rudder action. Some work has been done on this (van Hooff and Lewis, 1975), but it must be further developed.

Keane (1978) suggests that, "opportunities exist for improved course-keeping characteristics in aft-quartering or following seas, allowing for increased course flexibility during UNREP operations, and other, similar seamanship-critical operations."

Mandel (1967) states that "course-keeping ability may be specified quantitatively in terms of the stability index, of the characteristics of the Dieudonné Spiral Maneuver....or of the range of rudder angles used to maintain a straight course. In Gertler and Gover (1959) it is suggested that an attempt be made to design all ships for a stability index of zero or less, but it is recognized that this may not be practicable

for all ships." Actual numerical requirements that will insure good performance at sea remain in doubt.

Regardless of hull and appendage characteristics, good steering at sea in all weathers depends greatly on the design of the control system. For both naval and merchant ships it is wasteful to have stand-by manpower at all times to take over from the autopilot when rough seas reduce its effectiveness. All-weather steering is a problem of control as well as ship design, and it requires a system that will maintain optimum heading under all sea conditions and ship's courses.

Finally, hull design and control system must be such that broaching is avoided under even the most severe following and quartering sea conditions. (See section on Survivability.) Intimately related to steering, because of coupling between yaw and roll, is the control of rolling, which will also be discussed in this section.

Steering in Bow Seas

It should be noted that in head and bow seas we are not primarily concerned with yawing, which is a comparatively high-frequency oscillation about a *mean* heading that need not and cannot be restrained. Our concern is for the slower variation in leeway angle resulting from the irregularity of the sea. Model tests in regular oblique seas have shown (Lewis and Numata, 1960; Vossers, et al 1960) that there is a characteristic leeway angle for each combination of speed and heading. Consequently, when many wave components are present simultaneously — as in the case of real short-crested irregular seas — the ship will continually change its heading to the sea unless controlled by rudder action. Hence, the control system must be designed to:

- Oppose the low-frequency heading changes, but
- Allow some falling off of the bow to ease ship motions, as a human helmsman would do.
- Avoid rudder response to high-frequency yawing, since there is not time for the hull to respond and added resistance would result. The customary "dead band" provision is too crude, and filtering of input signal is probably required (van Hooff, and Lewis, 1975).

Salvesen (1974) has investigated the causes of the observed leeway angles in oblique waves, and states, "In the horizontal modes of motion the ship will experience steady drift motions in addition to periodic motions, because of the lack of hydrostatic restoring forces and moments in these modes. Similarly, in irregular seas a ship will experience slowly varying surge, sway, and yaw motions with non-zero means in addition to motion with frequency components equal to the frequency of encounter of the individual wave components....The drift and slowly varying motions are caused by wave excitation which is of higher order according to the conventional formulation of ship motion." Thus leeway angle in oblique seas, as well as added resistance at all headings, requires a more advanced second-order theory. "It should be recognized that the motions resulting from second order slowly-varying excitation can be determined from equations of motion which are otherwise linear because the motions may be assumed to be linear even though the excitation is non-linear." Salvesen is developing such a theory for regular oblique waves. The final step will then be to apply it to irregular waves. "As Newman (1974) has recently shown, the slowly varying exciting forces and moments in irregular seas, which are caused by the interaction between the difference frequency components, can also be directly obtained from the steady-state forces in regular waves."

This theory should be further developed and applied, along with the development of improved automatic control systems.

Steering in Following Seas

Problems in steering have also been observed in high-speed ships in following and quartering seas. In these conditions, frequencies of encounter are very low, especially with the longer overtaking waves. Hence, a number of new factors enter in:

- There is significant coupling between yaw and roll, as reported long ago by de Santis and Russo (1936).
- There is significant coupling between pitch and yaw, as a result of continually changing lateral coefficients as the ships pitches (Korvin-Kroukovsky, 1961).
- There are significant changes in lateral stability (GZ), in long waves and at high ship speeds, which affect roll and hence yaw (Paulling, et al 1974).

- The rudder has a large effect on roll (or heel) as well as on yaw, and hence the design characteristics of the automatic control system are critical (Taggart, 1970) (Eda, 1978).

Du Cane and Goodrich (1962) gave a good general overview of "The Following Sea, Broaching and Surging," which pointed out the importance of course stability and good autopilot design. Model tests in following waves demonstrated "the large range of wavelengths over which the model was carried along at the wave crest speed."

Wahab and Swaan (1964) investigated theoretically the problem of coursekeeping and broaching in following seas by concentrating on the above limiting condition of ship's speed equal to wave velocity (zero frequency of encounter). They assumed as self-evident that difficulty in steering — and ultimately broaching — is caused by dynamic course instability. They concluded that "all unsteered ships appear to be unstable somehwere on the downward slope of a wave." Hence, they consider the characteristics of the autopilot to be very important. Nevertheless, "a reduction of the danger of broaching can be attained by increasing the course stability of the ship in smooth water." However, no one has been able to specify exactly how much course stability is enough. In fact, some writers claim that a superior control system can overcome instability.

Steering problems are accentuated on modern high-speed ships. Taggart (1970) reported: "An unusual combination of circumstances occurring during an Atlantic crossing of a high-speed containership created a situation where the rudder, acting in response to automatic steering control demands, caused excessive ship rolling. Further investigation revealed the existence of an unstable condition due to a combination of asymmetrical hydrodynamic and mechanical characteristics and the interrelationship of ship motion and control actuation. Similar response has been noted on other high-speed vessels and is a cause for major concern in future containership operations."

He found that "under the conditions existing during the winter crossing, the self-excited yaw period was shorter and the roll period longer with the ratio between them approaching 2:1. Thus all of the ingredients for synchronous ship and rudder motion were present and only a small external excitation was required to aggravate the situation.

"Because the rudder moves with a fixed rate pattern, the amplitude which it can attain is a function of the control demand frequency, which in turn is a function of the yaw frequency. In other words, when the yaw frequency becomes too great the rudder cannot reach the ordered angle before it receives a signal to swing in the opposite direction. Thus, under rudder excitation, the roll builds up to an amplitude where the rudder beings to lag behind and to oppose the rolling motion. The rolling then subsides until the rudder can catch up with it and a new cycle of excitation and buildup begins. As a result, a repetitive pattern of increasing and decreasing roll amplitude is established."

In another high-speed containership, rudder action caused excessive heel angles and the difficulty was overcome by limiting the rudder angle. But a more basic approach is clearly needed, such as the theoretical study by Eda (1978), which should be pursued. Going further, however, it must be recognized that the rudder can not only cause rolling but can oppose it. Introducing a roll angle input permits a control system that will oppose both roll and heading deviation. A trial installation on a U. S. Coast Guard cutter has shown very promising results.

A novel method of evaluating changes in the automatic control system was developed at Webb Institute and evaluated on a model of the SL-7 containership, as reported by van Hooff and Lewis (1975). The model with its steering gear and rudder provided an analog of the ship when run in calm water in following waves. The control loop was closed by means of a digital computer in which the coefficients in the control equation could be determined under different conditions. This approach could be pursued further.

Eda and Crane (1965) presented a linear theory of sway and yaw for describing ship maneuvering and steering, in which rudder forces are accounted for by incorporating a restoring term proportional to yaw deviation and an additional damping term proportional to yaw rate. However, in the case of motions in following and quartering seas, no rudder effects are included. A more advanced treatment by Pérez y Pérez (1974) includes non-linear rudder forces associated with an auto-pilot, and obtains excellent time domain solutions. Although rolling is included, results for this mode are not satisfactory. Finally, Eda (1978) has

developed linear coupled equations of yaw, sway, roll and rudder action to describe the maneuvering and course-keeping behavior of high-speed ships such as destroyers. Some of the coupling coefficients were obtained from captive model tests on a rotating arm. (No account was taken of coupling of pitch into yaw). Some calculator simulation runs reproduced the rolling problems observed during high-speed runs in following seas as a result of low yaw - roll instability — especially if GM is low. Presumably these equations could be applied to more detailed studies of steering in following seas.

The theoretical approach of Paulling, et al (1974) (also Chou, Oakley, Paulling, et al, 1974) is particularly promising. (See also the section on Survivability). Quoting from Salvesen (1978), "J. R. Paulling has worked for several years on the nonlinear problem of large-amplitude ship motions in following and quartering waves. With the assistance of some of his students, he has developed a time-domain numerical simulation technique (Paulling, et al 1974) which has been used to predict even the very nonlinear phenomena of capsizing. In this method the forces due to body-generated waves (i.e. added mass, damping, and diffraction) are assumed to be small due to the low encounter frequency and therefore are estimated very crudely; the hydrostatic forces are assumed to dominate the problem and are computed to a high order of accuracy for the actual instantaneous submerged hull shape. The good agreement between computational and experimental results shown seems to indicate that this time-domain numerical method may not only be a useful tool for predicting capsizing but it may also be useful for the general dynamical problem of ship motions and course-keeping at low encounter frequencies. Since strip theory is not applicable in the very low frequency range, I find it surprising that this method has not gained a wider recognition."

Full-scale data on ship steering are also needed, covering rudder angles, rudder rate (steering gear power), yaw angles under different conditions and with different auto-pilot adjustments.

Control of Rolling

For design purposes the interest is not only in the prediction of rolling (as discussed in the chapter on Ship Motions) but in designing and evaluating the effectiveness of anti-rolling devices. The state

of the art is well summarized in two recent papers, covering bilge keels, activated fins and passive tanks:

Cox, G. G., and Lloyd, A. R. (1977), "Hydrodynamic Design Basis for Navy Ship Roll Motion Stabilization," Trans. SNAME, vol. 85.

Barr, R. A., and Ankudinov, V. (1977), "Ship Rolling, Its Prediction and Reduction Using Roll Stabilization," Marine Technology, vol. 14.

An interesting development is the use of the rudder for roll reduction. A trial installation on a Coast Guard cutter has been quite successful. See also Cowley and Lambert (1972).

As a matter of fact, control of roll and of heading are intimately connected because of the strong roll-yaw couplings, particularly in following and quartering seas. As shown by Gatzoulis and Keane (1977) it is of vital importance to be able to evaluate the seakeeping performance of a new design in the early stages, both with and without anti-rolling equipment. A sample comparative evaluation for a small frigate made use of a one-degree-of-freedom computer program (Cox and Lloyd 1977), based on Conolly (1969) for both fin-stabilized and unstabilized roll at all headings. A second evaluation for a large cruiser made use of a three degree-of-freedom program (Hydronautics) based on Webster (1967) and Barr and Ankudinov (1977). Gatzoulis and Keane (1977) point out that there are many shortcomings in the above procedures. Both methods "use a quasi-linear approach to solve a very non-linear problem (i.e., predicting roll motions). For example, correction factors are applied to the DTNSRDC program in order to compensate for deficiencies in the single degree-of-freedom approach which ignores the cross coupling effects of yaw and sway. On the other hand, the Hydronautics program accounts for the cross-coupling effects for three degrees-of-freedom, but available methods for estimating the roll damping coefficients are very empirical and less satisfactory, since roll damping is of viscous nature and potential theory is not applicable."

Hence, it may be concluded that despite recent progress in the state of the art of controlling roll, the importance of this subject for naval ships calls for further study and refinement of design and evaluation techniques. Meanwhile, model tests can be of great value in validating the design and checking the predicted effectiveness of stabilization systems.

Control of Pitch

The use of fins for reduction of longitudinal motions (fixed at bow or controllable at stern) have not been given much attention recently but should not be overlooked. Abkowitz (1959) gave a comprehensive report on the subject, giving both a theoretical analysis and results of extensive model tests in waves. He concluded that fins showed real promise and recommended their installation on ships in service. However, Cummins (1959) in discussion indicated that an actual installation of bow fins on the modified Mariner USS Compass Island had revealed severe vibration problems, "and no operator will consider installing fins until he is assured that this fault has been corrected."

Subsequently, Ochi (1961) made a thorough experimental and theoretical study of the fin-induced vibration problem. He explained the reason for the vibration and found that "a fin having holes of proper size and shape (Fin X) appears to be beneficial for both pitch reduction and vibration prevention." In discussion, Abkowitz (1961) disagreed with the author's explanation of the phenomenon and stated that "a major part of the vibration was caused by the slight time differential in the collapse of the ventilated bubble on the port and starboard sides." Consequently, model tests showed that equalizing holes cut through the bow "have a substantial effect in reducing bow vibrations."

The question should now be asked as to whether or not some of the above suggested remedies — or others not yet considered — might make fixed bow fins feasible for practical use. The possibility of controlled fins at the stern (where angles of attack for fixed fins are unfavorable) should also be considered and evaluated.

Needed Research

The most urgent research need is to develop automatic steering systems that have all-weather capability at all headings to the sea. This involves not only the improvement of the control system itself, but a proper balance among hydrodynamic properties of the hull, design of rudder, design of steering gear and design of the control system. Studies are needed in theory, experiment and full-scale data collection.

There is a need to improve control of rolling, with simplification if possible at the same time — perhaps by utilizing the rudder instead

of separate fins for the purpose.

The possibility of pitch reduction by means of damping fins should also be reevaluated. See also Conolly and Goodrich (1970) and Kaplan and Goodman (1964).

Chapter 4

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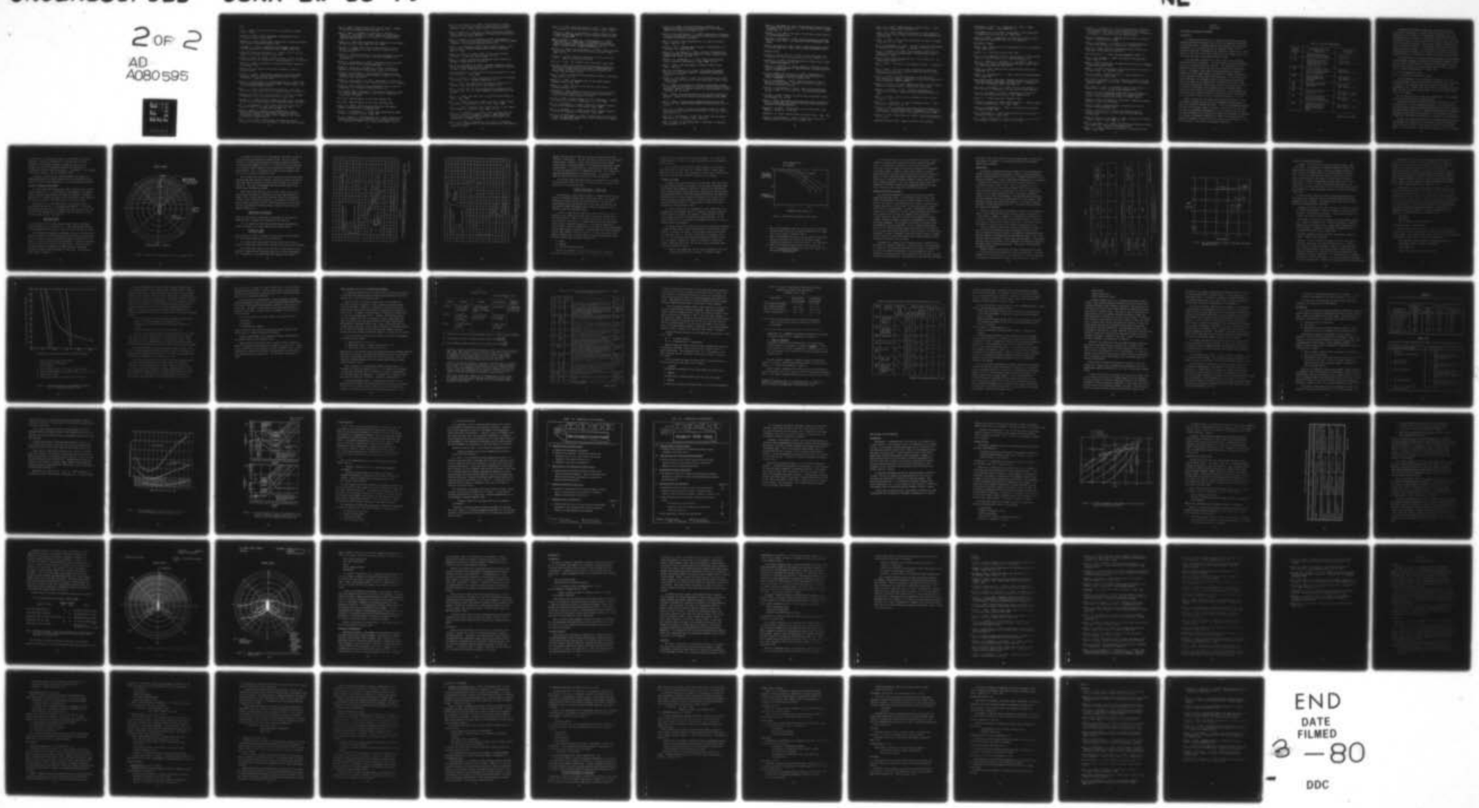

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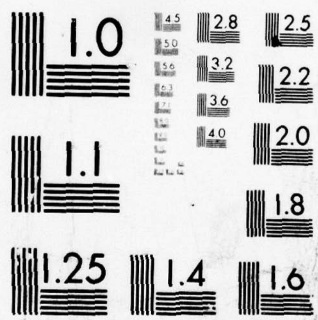

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Chapter 5

APPLICATIONS

EVALUATION OF SEAKEEPING PERFORMANCE

Introduction

It is generally agreed that it is essential to be able to assess the seakeeping performance of naval ships, or their environmental operability, in the design stage. A complete and precise evaluation of the seakeeping performance of a ship design may require a detailed study of how its "combatant capability" is degraded by sea conditions (Prout, et al, 1974). However, in the early design stages, when detection and weapon systems may not even be selected, a more general method is needed.

In the philosophy developed by St. Denis (1976), such performance evaluation involves two aspects: "an index by which to measure performance and a set of criteria by which to judge it." The indexes and criteria depend on the ship's mission, but there may be several criteria for each mission. For example, sonar search mission performance may depend on probability of sonar dome emergence, on vertical or lateral acceleration at a sonar operator's station, and on attainable speed. A criterion must be set up which specifies acceptable values of each applicable performance index or of some sort of combined index. Quoting from St. Denis (1976), "The obvious problem that arises is that of giving the proper weight to all the indices of performance and of emerging with an integrated overall evaluation of the system's environmental operability. This weighting and integration can be carried out only by relating the process to the mission of the system." See Table 6 for typical missions (Johnson, et al, 1979).

"Given a mission and a sea-based system by which to fulfill it, the environment of weather and sea will tend to degrade the effectiveness in which the system will perform the mission. It is this environmental degradation that is the central subject of inquiry. Since in airs and seas that are calm the environmental degradation is nil, the system's calm air and calm sea performance of its mission can be taken as the standard of reference. By so doing, environmental operability is defined as and measured by the degree of attainment of calm air and still water mission performance. It is this ratio that is the index of environmental operability.

TABLE 6 - TOP LEVEL REQUIREMENTS

Mission Area	Requirements Operational Capability	Environmental Condition
MOB	Underway Replenishment and strikedown day/night	Sea State 5 (sig. wave ht = 10.2')
MOB	Continuous and efficient operation (other than replenishment and helicopter operation)	Sea State 6 (sig. wave ht = 16.9')
MOB	Limited operation, capable of continuing mission after sea subsides	Sea State 7 (sig. wave ht = 30.6')
MOB	Must be capable of surviving sea state 8 and above	Sea State 8+ (sig. wave ht = 51'+)
ASW & SUW	Operation of embarked helicopters	Sea State 5 (sig. wave ht = 10.2')
ASW	Sonar Dome detection capability	Wind Speed = 15 Knots Ship Speed = 15 Knots
AAW	Continuous & efficient operation of weapons systems (other than helos)	Sea State 6 (sig. wave ht = 16.9')
SUW	Continuous & efficient operation of weapons systems (other than helos)	Sea State 6 (sig. wave ht = 16.9')

Johnson, et al (1979)

"Environmental performance changes with sea state and weather. For an overall assessment of a system's nautical qualities it is the expected long-term average of its environmental performance that is to be introduced in the evaluation. By long-term is meant in this context a meaningful interval of time related to the mission of the system. This can be the mission's duration or the expected lifetime of the system or other justifiable run of time. To some extent, lifetime averages can be replaced by yearly averages. The environmental performance in each sea state weighted by the frequency of occurrence of such sea state over the long-term interval is defined as the system's environmental operability."

"This operability is assessable provided the system has been designed to have adequate strength to withstand the disturbed environment of wind and waves and is so operated as to minimize the environmental risk to which it may be subject. The qualification that the system is operated so as to minimize environmental risk implies that:

a) It can be manned with safety.
b) It is responsive to directional control.

"The environmental risk is assessed with reference to a set of limiting conditions jointly termed condition of survivability. When such a condition is attained with ample margin, there is no concern over environmental risk. However, when the condition is not attained, environmental operability ceases to be meaningful, for the life of the system itself is in jeopardy."

For the present we shall assume that survivability is not a problem, and it will be discussed in a separate section.

As pointed out by Hadler and Sarchin (1974), habitability is also a consideration in a ship's seakeeping evaluation. It is important for the crew's health, safety and morale that, regardless of mission, exposure to excessive motion be minimized. Some data are available on accelerations associated with discomfort and seasickness. For the present it will be assumed that limitations of operability will provide also for habitability.

We shall also assume the availability of adequate wave spectral data (see chapter on Environment) and of satisfactory methods for predicting a ship's behavior in terms of accelerations, relative motions, added power, etc. as a function of ship speed and heading and of sea severity,

as defined by its spectrum (see chapters on Ship Motions and Derived Responses). Hence the performance of a particular design can be determined and displayed in tabular or graphical form — as, for example, by a series of speed-polar diagrams for different sea conditions (significant wave heights) and — if necessary — for different conditions of loading. See Fig. 5 (NAVSEA, 1979).

In the next section we shall consider indexes for judging seakeeping performance on different missions and in the following section specific criteria of such performance — or of environmental operability.

Indexes of Seakeeping Performance

St. Denis notes that for many naval ships, mobility is the "primary nautical quality" — i.e., the criterion of performance is the "degradation of speed with sea severity in the area of operations." Missions falling in this category are simple transit from point to point (mobility) and exercises in which a ship must be able to sail with a fleet.

Where mobility is the primary factor, the appropriate index of environmental operability — or seakeeping performance — is the ratio of average speed made good to calm water speed for a specific route, considering actual headings and sea conditions on that route, over a long or short period of time. The index is,

$$\frac{\text{Average sea speed}}{\text{Calm water speed}}$$

St. Denis (1976) calls this the "expected speed fraction" and Mandel (1979) identifies it as "box score" no. 2. This index applies directly to most merchant vessels, as well as to naval vessels on transit missions.

The evaluation of seakeeping performance on the basis of speed alone requires consideration of both voluntary and involuntary speed reductions. The first requires criteria for acceptable levels of accelerations, roll angle, etc. affecting habitability, and frequency of slamming or shipping of water, affecting the safety of the ship itself. (See next section). The second requires consideration of added resistance, propulsive efficiency and power plant performance in rough seas. (See section on Power in Waves, Chapter 4).

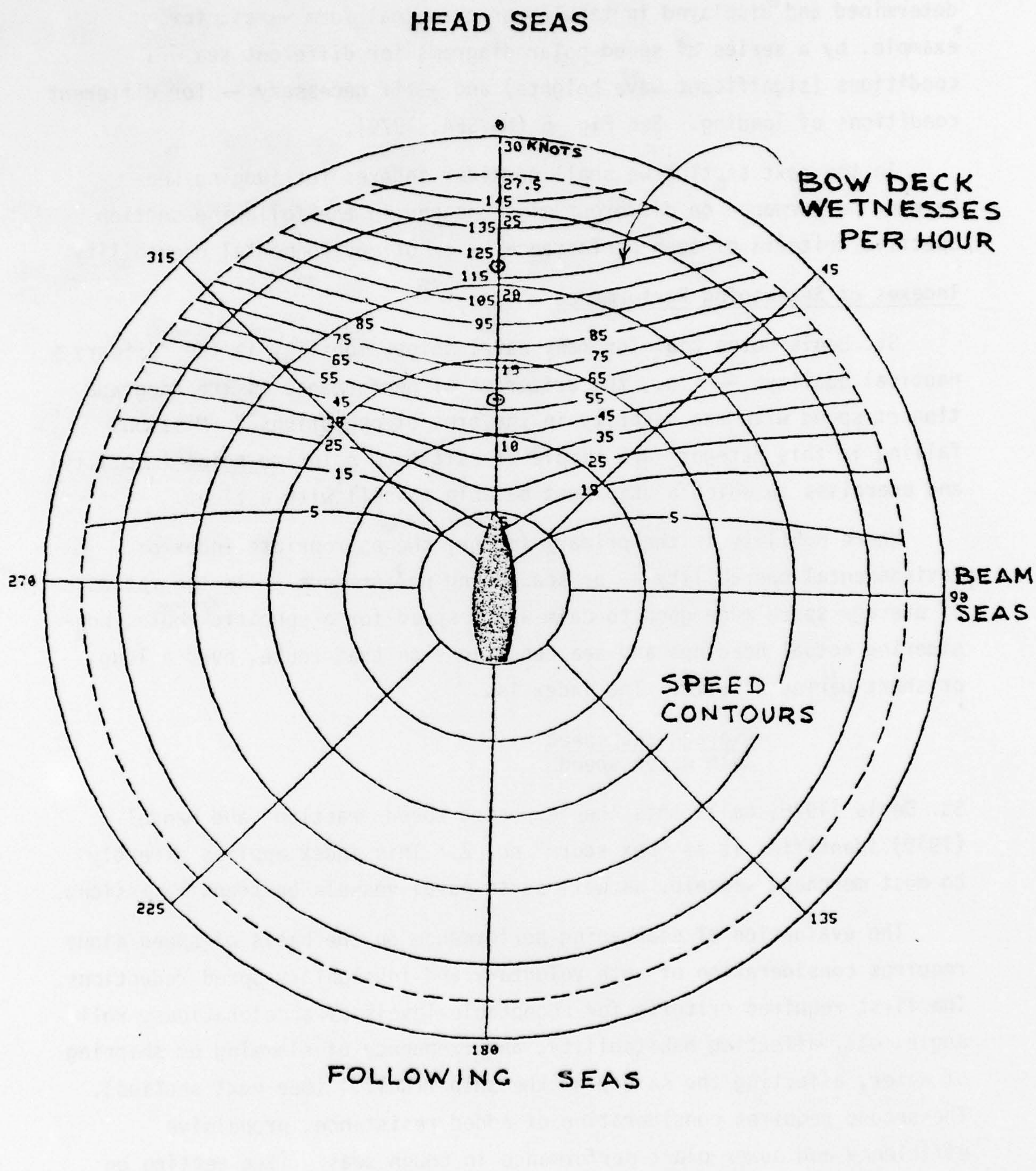


Figure 5. Sample Polar Diagram for FF-1052 Class (NAVSEA 1979).

A graphical application of this approach was developed and applied by Olson (1977) and summarized by Mandel (1979). The plots show on the basis of significant wave height the limiting speeds corresponding to the governing seakeeping criteria. In order to allow for variations in sea spectral shape, separate curves are plotted for different ship/wave headings. This is illustrated for simple transit between points in Fig. 6 for head seas (from Olson, 1977).

But for many naval missions, such as strike and tactical operations, including ASW, AAW, logistical support, recovery and rescue, the mission itself may impose limitations on ship motions and hence on attainable sea speed. The index of performance must then consider both mission effectiveness and attainable speed.

Olson (1977) dealt with the case of simple transit plus a sonar search mission by adding the condition of no sonar dome emergence, as shown in Fig. 7, which reduced the attainable speed for the monohulls. St. Denis (1976) carried the evaluation a step further on the basis of work of Hamlin and Compton (1970). After determining a limiting speed for each sea condition and ship heading, he gave the index of environmental operability as,

$$\frac{\text{Search rate in rough seas}}{\text{Search rate in calm water}}$$

where the search rate in rough seas is the product of sea speed and detection radius integrated over heading and sea condition.

If it is assumed for preliminary design purposes that detection radius is constant, this index reduces to the previous index,

$$\frac{\text{Average sea speed}}{\text{Calm water speed}}$$

where average sea speed is obtained by averaging with assumed probabilities for ship/wave headings and for sea conditions.

For variable depth sonars towed from the stern the criterion is vertical acceleration at the stern in relation to the cable system strength.

On the other hand, speed is not essential to some missions, such as electronic communications, helicopter operations, at-sea replenishment, etc. Furthermore, it has been pointed out (Leopold, 1978), that "it

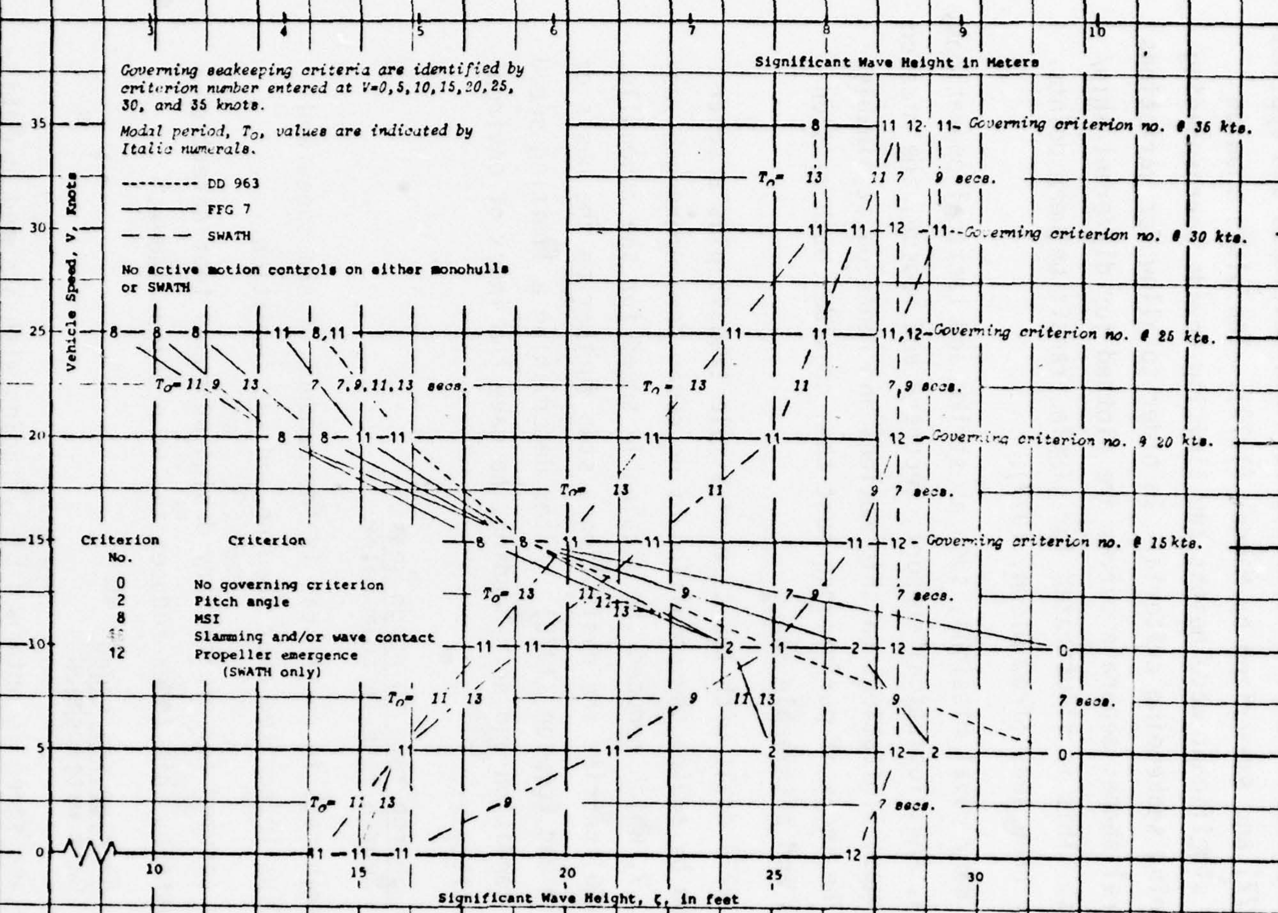


Figure 6

Limiting significant wave heights and governing seakeeping criteria in head seas for FFG-7, DD-963, and 3350-ton SWATH for the transit alone function

Olson (1977)

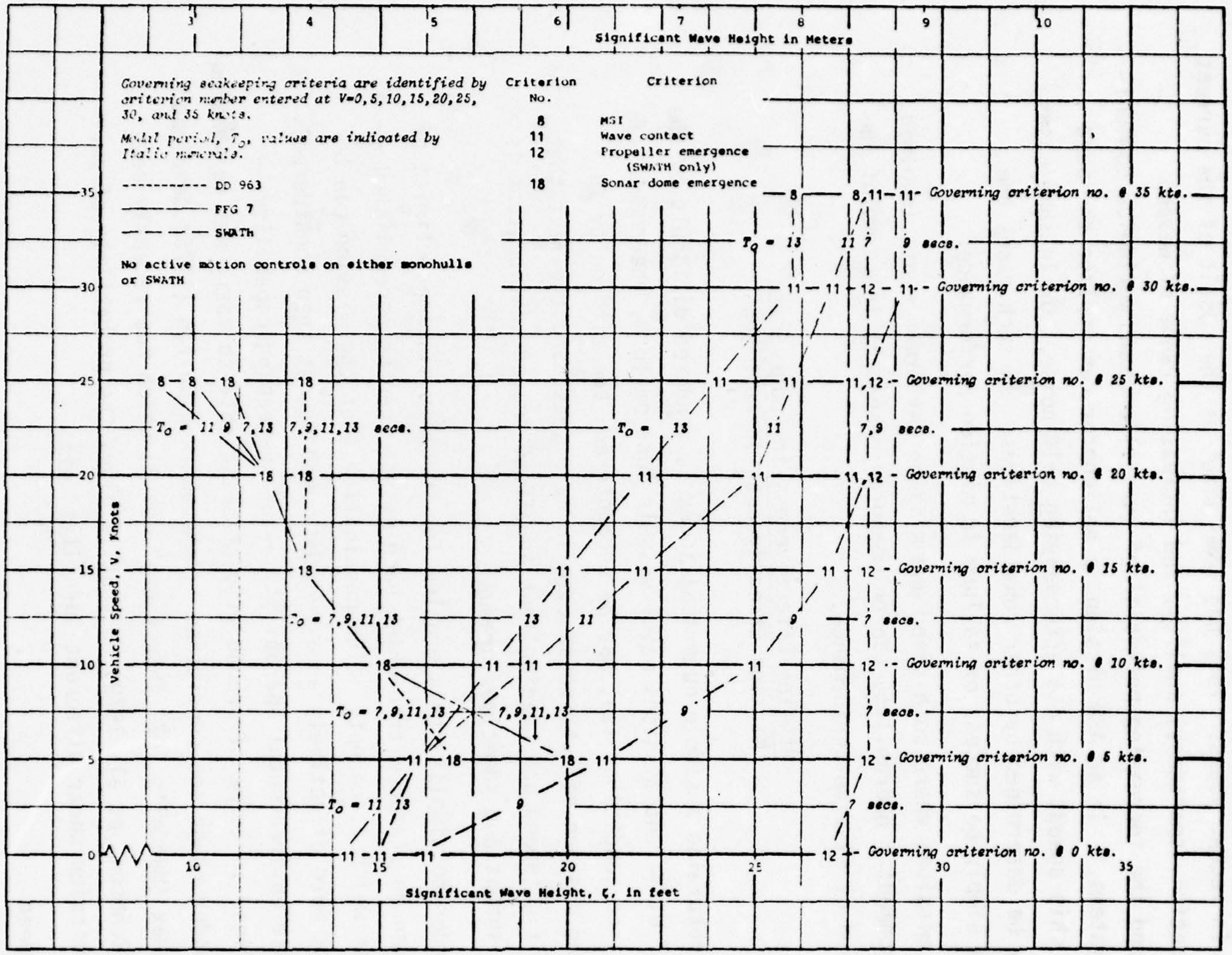


Figure 7

Limiting significant wave heights and governing seakeeping criteria in head seas for FFG-7, DD-963, and 3350-ton SWATH for the transit plus sonar search function

appears that the value of speed has actually decreased for many naval missions in recent years. This has come about as the result of the current sophistication, smartness, agility, and increasing range of weapon systems and the increasing potential of surveillance and worldwide communication systems." In an ASW mission, a helicopter can replace the need for high ship speed, with its accompanying self-noise. Or in some cases speed may be determined by other considerations. In such cases the index may simply be success or failure in mission performance.

For missions where both speed and mission performance are involved, the environmental operability can be measured generally in terms of the degredation of mission performance,

$$\frac{\text{Mission Effectiveness in Rough Seas}}{\text{Mission Effectiveness in Calm Seas}}$$

But obtaining a simple numerical index is rendered difficult by the variety of different missions naval vessels must perform, the number of different sea conditions that may be encountered, the difficulty in quantifying mission effectiveness even in calm seas, and the fact that ship handling (speed and heading) has an effect on degredation that is sometimes abrupt and sometimes gradual.

In order to simplify this problem for specific missions, limits of behavior can be stated within which each mission can be accomplished — and without which it cannot. (The possibility that the mission can be carried out more effectively at a reduced speed is not then considered). In this case environmental operability — or seakeeping capability — can be defined in terms of probability of being able to carry out designated missions under rough sea conditions. Comstock and Covich (1975) developed such an index (Mandel's 1979 "box score" no. 3) which has recently been modified (Johnson, et al, 1979) so that it gives the probability of performing a mission under different "profiles" of:

a) speed

b) heading

c) sea condition (wave height)

The index is obtained from basic polar diagrams which show the situations in which specific missions can and cannot be performed, as

functions of speed, heading, sea state (and loading). The criteria for judging whether a mission can or cannot be performed will be discussed in the next section.

Thus, in effect, the new Comstock index (Johnson, et al, 1979) is a more general form of "box score" no. 1 (Mandel, 1979), in which speed need not be held constant. Bales advocates a similar index in which both wave height and wave modal period are considered as parameters.

A Generalized Index

It appears that the Comstock mission performance index could easily be made flexible enough to accomodate all of the above variations simply by avoiding fixed assumptions regarding a "speed profile". Performance index could be plotted against speed, with reasonable assumptions regarding the probabilities of different headings and different sea conditions. Then evaluations of mission seakeeping performance can be made with different assumptions regarding speed — a single, optimum speed, maximum average attainable speed, or a "speed profile" of equal (or unequal) probabilities between certain limits.

It should be noted that the assumption of equal probability of all headings may not be appropriate for all missions, and other assumptions could be made in the above. For example, it might be best to select only the best heading for evaluating helicopter operations. Or one heading relative to the sea should be considered in the case of aircraft carrier takeoffs and landings.

For greater generality, without restriction on assumed sea conditions, a number of index curves can be plotted against significant wave height, each for a different ship speed. In other words, plots could be made of performance index vs. sea state, with speed as a parameter. (See Fig. 8). For each speed, the maximum significant wave height in which it is attainable — whether as a result of voluntary or involuntary limits — should be identified. One can then assess performance under a variety of conditions, such as:

1. What is the probability that the ship can perform a particular mission in Sea State 6 at 25 knots? At reduced speed?

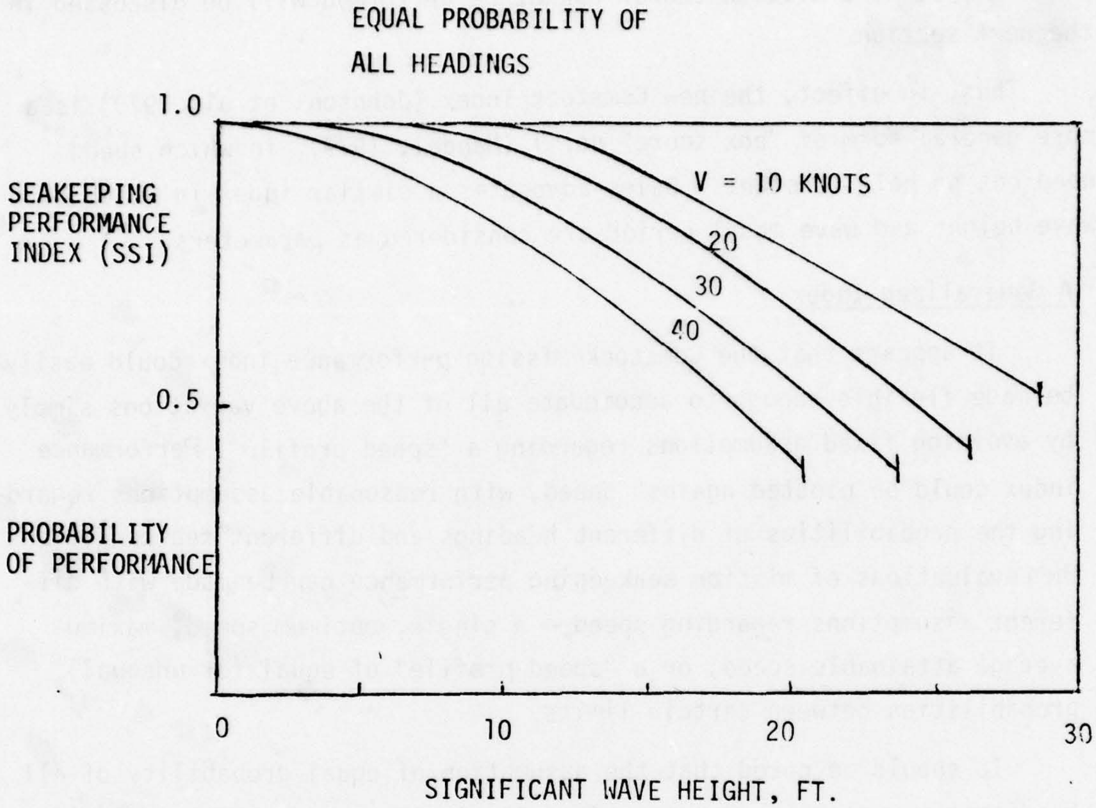


Figure 8. Hypothetical Performance Index Curves

2. What is the probability that the ship can perform a particular mission in Sea State 6 with an equal probability of all speeds from 10 to 25 knots? (Comstock index)
3. What is the probability that the ship can perform a particular mission at 25 knots over a period of time with a stated probability distribution for sea conditions? (1st "box score")
4. What is the average attainable speed while carrying out a particular mission in specified sea conditions? Hence, what is the ratio, $\left(\frac{\text{ave. attainable speed}}{\text{design speed}}\right)$?

All of the preceding discussion indicates that, although a number of methods of evaluating environmental operability have been developed, there is no uniformity or agreement as to the best procedures. Some broad discussions among ship designers, operators and researchers are urgently needed. Perhaps a study could be made of a suitable generalized index, and trial plots could be made of the type described above, in order to determine whether indeed they do permit greater flexibility in selecting performance indexes to answer specific questions about alternative designs. If so, the scheme and others should be presented to all those involved in the seakeeping evaluation of naval ships, discussed, and a single basic procedure agreed upon.

Combatant Capability Assessment

An interesting development in recent years has been Combatant Capability Assessment (CCA). As explained by Eckhart (1974), "Navy planners and operators must be able to evaluate combatant capability which can be realized in operating practice in order to relate resources invested (manning as well as dollars) in ship acquisition to system definitions for design guidance. In order to meaningfully evaluate capabilities, the dynamics of the ship system environment and the variability imposed by the 'at-sea' environment must be considered ...." In short, among the many factors affecting the capability of combat systems — hardware, software, personnel, electromagnetic environment, and threat engagement — the responses of the ship to its wind and sea environment are of basic importance. CCA is a sophisticated process (Prout, et al, 1974), involving complete specification of the ship and all its systems and detailed operations research analysis of effectiveness. Therefore, it cannot be employed in the early stages of design. However, detailed studies of actual ship systems would provide guidance for more approximate approaches early in design.

Consequently, it appears that a research project to establish the degredation of combatant capability on several ships on several missions, as a result of sea conditions, would be of great value. It should serve to clarify the relative importance of various seakeeping criteria discussed in the next section, such as angles of roll and pitch, vertical and lateral acceleration, etc., and might even reveal some new, overlooked

criterion. Such a study might also provide some guidance in formulating more effective procedures for seakeeping performance (environmental operability) assessment.

Benefit/Cost

An important area mentioned briefly under CCA is the development of methods of making benefit/cost studies of overall mission effectiveness against financial outlay or life-cycle cost. Technical evaluation of seakeeping performance — or level of environmental degregation of performance — is important, but should be carried further to permit comparison of alternative design in terms of cost. The basic elements of such a study were carried out by Gatzoulis and Keane (1977) for the case of the installation of active fin stabilizers on a class of frigates with respect to a helicopter operation mission. The overall evaluation (Table 7) was in terms of percentage of time that helicopter operations could be performed with certain assumed profiles of ship speed vs. time, heading to the sea, sea state (North Atlantic) — up to and including sea state 7 (significant height 30.6 ft). The cost of the installation was stated to be $800,000.

One way of relating cost to performance is given in the accompanying Figure 9, which shows an extreme case in which a small cost results in a large benefit. However, a change in ship dimensions (particularly an increase in length) or an increase in bow freeboard might in some cases also show large benefit for relatively small cost. A reference line has been added to show the trend of effectiveness proportional to cost.

A serious problem in putting the preceding procedures into effect is the difficulty of estimating mission effectiveness and costs at the early pre-feasibility stage of design. Consequently, some detailed after-the-fact analyses of representative designs that have become actual ships might be useful for guidance in future early-design studies. Such detailed analyses might be carried out in the framework of the Combatant Capability Assessment process mentioned previously. (Some work is now being done by Hawkins and Prout).

Another reason for carrying out the above proposed detailed studies is to provide some concrete benefit/cost data for seakeeping. A few good examples or case studies would clarify the question of relative importance of seakeeping research and the value of early application in design.

TABLE 7

a) PREDICTED FIN STABILIZER EFFECTIVENESS FOR A SMALL FRIGATE

HELO OPERATIONAL EFFECTIVENESS	IN SEA STATE 5	IN SEA STATE 6	IN SEA STATE 7	ALL YEAR AVERAGE IN NORTH ATLANTIC
WITHOUT FIN STABILIZERS	45%	20%	0%	50%
WITH FIN STABILIZERS	95%	95%	30%	90%

b) PREDICTED FIN STABILIZER EFFECTIVENESS FOR A LARGE CRUISER

HELO OPERATIONAL EFFECTIVENESS	IN SEA STATE 5	IN SEA STATE 6	IN SEA STATE 7	ALL YEAR AVERAGE IN NORTH ATLANTIC
WITHOUT FIN STABILIZERS	100%	45%	15%	75%
WITH FIN STABILIZERS	100%	95%	30%	95%

Gatzoulis and Keane (1977)

Notes: Sea States 5, 6, and 7 are represented by significant (average of the one-third highest) wave heights of 10.2 feet, 16.9 feet, and 30.6 feet, respectively

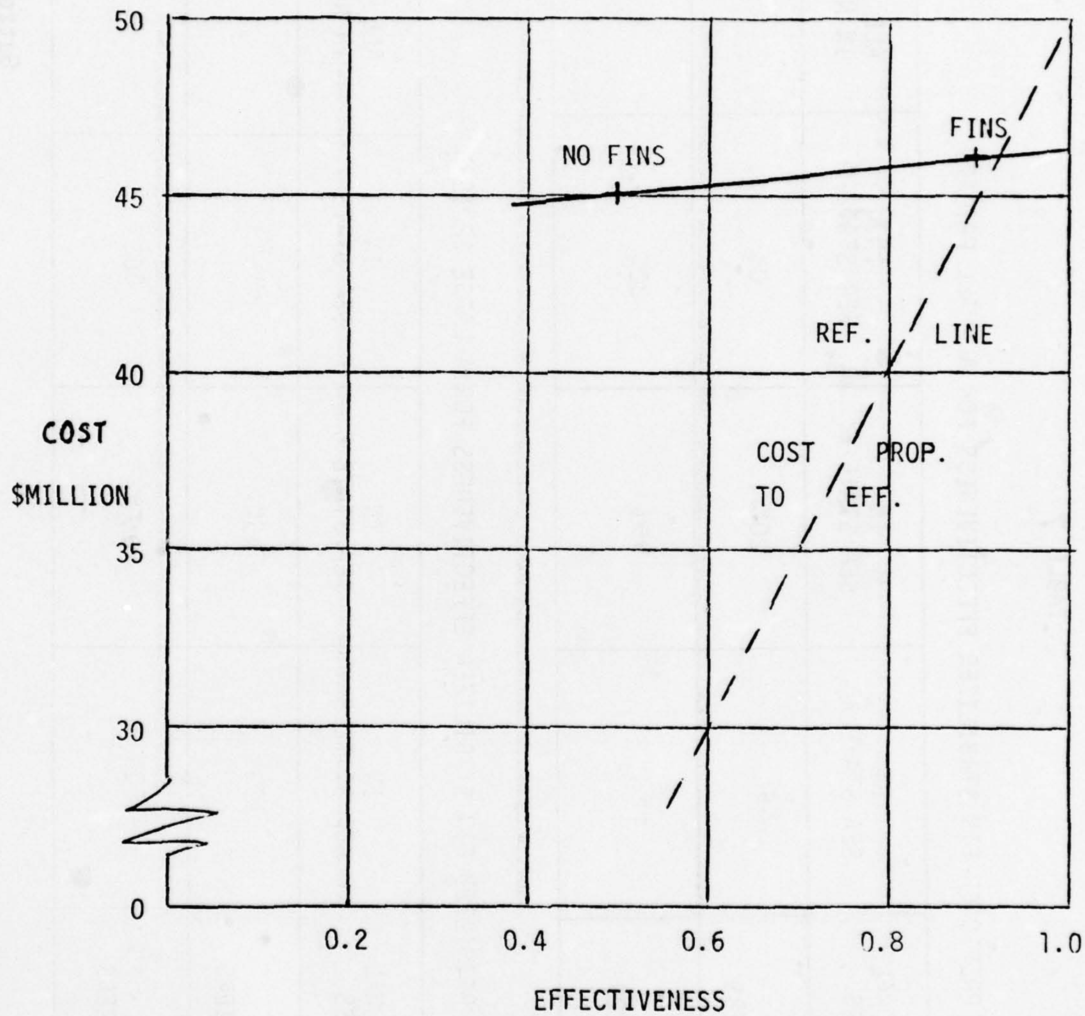


Fig. 9. Cost Effectiveness of Frigate in Helicopter Operations (Based on Table 7).

Criteria of Seakeeping Performance

In Chapter IX of Principles of Naval Architecture (Lewis, 1967) it was stated: "If predictions of attainable speed in different sea conditions are to be made, specific limits of acceptable wetness of decks, severity of slamming and vertical accelerations are needed. This is as yet one of the unsolved aspects of the problem, and tentative limits for general cargo ships are offered here in the hope that they will stimulate the gathering of more reliable data for different types of ships." A modest beginning had been made by Crane (1961), but in the intervening years very little data have been acquired for merchant ships — with the notable exception of the work of Aertssen (1968, 1972).

For naval vessels, Hadler and Sarchin (1974) reported results of interviews with 6 commanding officers of destroyer-type ships and the commodore of their squadron. The principal factors limiting the ships' operational performance were identified:

- Slamming, especially on the side of the bow, as judged by resulting hull vibration (whipping). Concern for damage to hull or sensitive equipment. Minor effect on personnel. Stern slams experienced by smaller ships (DE) with large transoms.

- Deck wetness, particularly on forecastle, but occasionally further aft. Concern for damage to deck fittings and equipment, sometimes weapons, and for personnel injury. Spray creates footing and visibility problems. A sequence of incidents of shipping water was considered more serious than a single event.

- Vertical acceleration due to pitching (and heaving), especially forward. Affects crew performance.

- Rolling. ("It was estimated that about 50% of the time while in operation, these ships experienced troublesome roll.") Concern for damage to fittings and equipment, injuries to personnel moving about, reduced personnel job efficiency, wear on stabilized platforms for antennas, etc., functioning of missile launchers and sonar transducers, helicopter operation. All maintenance work is affected. Roll period, as well as amplitude, is a factor — suggesting importance of lateral accelerations. (Other writers emphasize vertical accelerations).

Performance criteria for naval ships depend greatly on mission. A report on "Ship Subsystem Performance Limitations" for NAVSEA by McMullen Associates (1976) as a followup to the Annapolis Workshop (NAVSEA, 1975) summarized available data on the degradation of mission performance of equipment, subsystems and personnel. Specific subsystems considered were helicopter operation, weapons, replenishment at sea and tracking. Rolling was found to be the most critical mode of motion, although in many cases pitch and heave were important also. Figure 10 is an example of a general guidance chart prepared for the DDG-47 (McMullen Associates, 1976, Fig. 2.2).

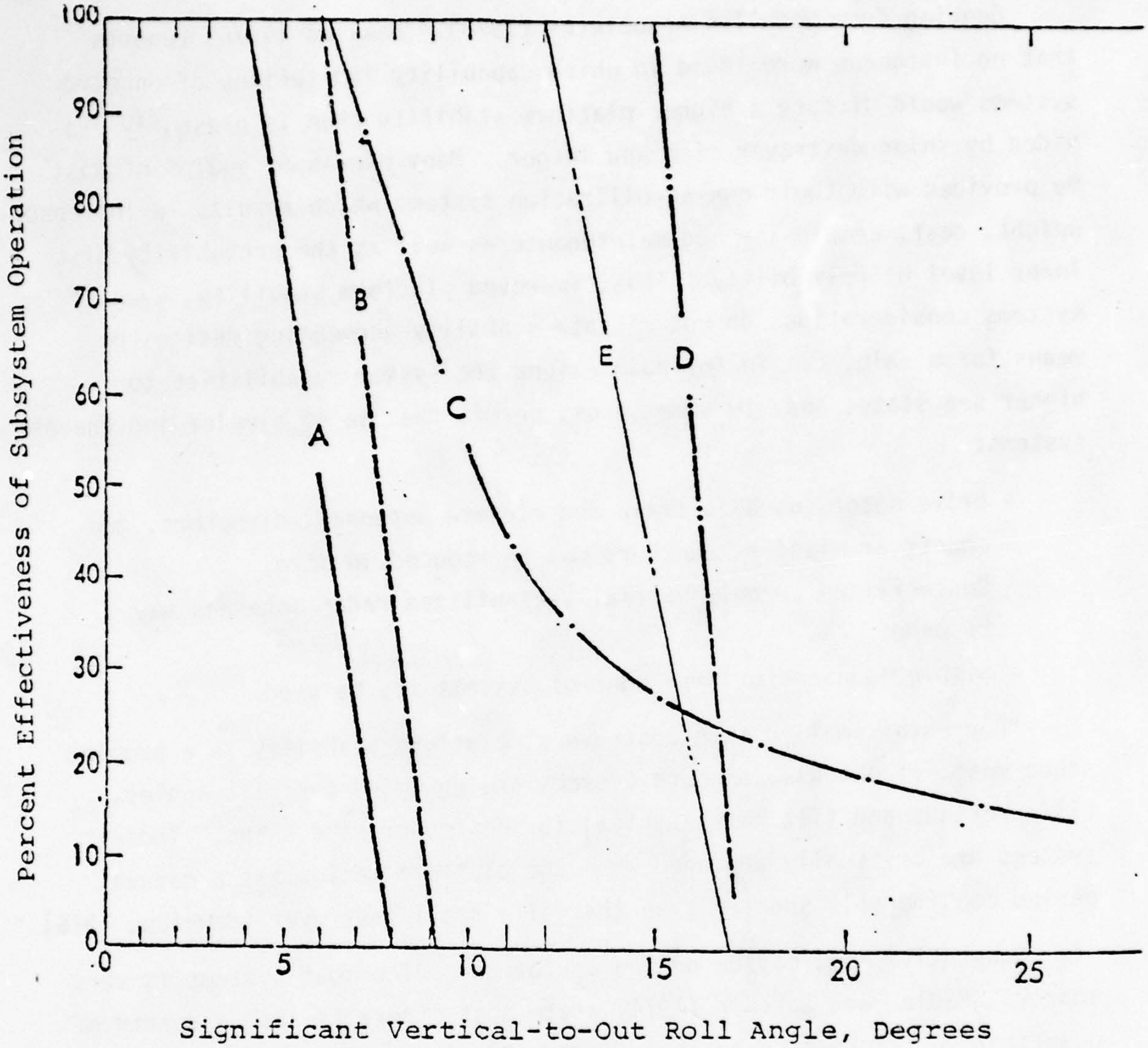
Considering some criteria associated with specific ship missions, Hadler and Sarchin (1974) discuss the effects of ship motions on helicopter landings and take offs, stressing the importance of roll angle. But McMullen Associates (1976) state, on the basis of ship/helicopter trials, "Of the six ship motions....the most critical was the combination of vertical and lateral motion caused by pitch and heave, and yaw and roll, respectively." Roll alone was not found to be critical because it could be successfully judged and allowed for by the pilots. In evaluating a ship's performance on a helicopter operation mission, Johnson, et al (1979) consider the following factors:

- Roll angle
- Pitch angle
- Vertical velocity at the landing pad

Some further study is clearly needed.

Shipboard combat systems require a stable base for accuracy in identification, acquisition, and weapons launch and control (Hadler and Sarchin, 1974). This involves several other factors besides roll amplitude, accelerations, and vibrations — as previously mentioned —:

- Hull deflection (which may give a significant difference in orientation between a tracker and a weapon).
- Gyro compass lag
- Target interference as a result of motions



A Missile and Torpedo Strikedown
HELO Handling (Manually)
HELO Landing

B HELO Landing/Take-off (Without RAST System)

C Human Effectiveness (Averaged over many activities)

D Refueling at Sea

E RAST System (HELO Hauldown and Traversing)

Figure 10. Subsystem Effectiveness Degredation for DDG-47
(Fig. 2-2, McMullen Associates, 1976)

Quoting from McMullen Associates (1976), "Hawkins (1976) reports that no instances were found in which capability limitations of onboard systems would dictate a higher platform stability than is presently provided by ships destroyer size and larger. Many pieces of equipment must be provided with their own stabilization systems which results in increased weight, cost, complexity and maintenance as well as the probability of a lower level of reliability. Thus, improved platform stability, even if systems considerations do not dictate stability-augmenting designs or means for a ship, can in any case extend the system capabilities to higher sea states and, in some cases, permit the use of simpler and cheaper systems:

- Drive motors used to train and elevate antennas, directors, gun mounts or missile launchers may be reduced in size.
- Unstabilized or only partially stabilized radar antennas may be used.
- Simpler gun and/or fire control systems may be used.

"For ships smaller than destroyers, platform stability is a problem since most, if not all, onboard systems are designed for tilt angles, tilt periods and tilt rates typical for destroyer size ships. These systems are critically degraded when the platform motion has a natural period considerably shorter than that of a small destroyer (Hawkins, 1976)."

Quantative information on the performance of combat systems is very scarce. Hadler and Sarchin (1974) state that "there is such a dearth of quantitative information on the effects of ship motion on equipment that only qualitative judgments can be made at this time."

Considering the sonar search mission, a more sophisticated approach than that of bow dome emergence (section on Indexes of Seakeeping Performance) was presented by Hamlin (1969), in which the principal criterion was the joint probability of sonar submergence when a "ping" was made and when an echo returned. A modification introduced by Olson (1977, 1978) is to consider that in order for sonar detection to be possible the sonar dome should remain submerged for a time interval

that covers both a ping and its return (a ping cycle). This led to the PSEPR/ping criterion (PSEPR = Positive Signal Excess Ping Return) which specifies the proportion of successive ping cycles in which no emergence should occur for successful detection.

Two other effects of ship motions on sonar performance have been studied by Schothorst (1976). One is signal attenuation due to pitch and roll of a ship with an unstabilized transducer, resulting in high losses in severe seas. The other is distortion of sonar echoes, which depends on length of a tone pulse. Further study is recommended, particularly on sonar distortion.

For aircraft carriers St. Denis (1976) set up the criteria of:

- No bolting
- No crashing
- No landing gear collapse

These involved vertical motion and velocity of various points on the carrier deck as a result of heaving and pitching.

Finally, replenishment at sea operations require consideration of the relative motion of two different ships.

Mandel (1979) also points out that, "A new criterion is needed to address the yaw-heel motion problem of monohulls in astern seas. Because no such criterion has been developed, current assessments of the seagoing performance of monohulls in seas that include moderate to severe stern seas are unrealistically optimistic." See section on Ship Control in Waves.

Numerical Data on Criteria of Seakeeping Performance

A summary of published data on actual figures associated with various criteria for both merchant and naval vessels was presented by Lloyd and Andrew (1977). See the accompanying Table 8.

Data on limits of naval ship response that are acceptable for different missions are essential to the seakeeping evaluation schemes discussed previously. Mandel has reviewed the situation recently for mono-hull and other types of naval ships, relying mainly on the work of Olson (1978). A summary of available data for monohulls and SWATH ships is given in the accompanying Table 9 (Mandel, 1979). Mandel cautions, "box scores depend on a host of seakeeping criteria, whose nature and whose prescribed values have been devised by individual investigators dealing with an individual vehicle type. These criteria and their prescribed values, therefore, not only lack the benefit of cross-fertilization but are one of the weakest of the three essential elements (criteria, seaway definition, response prediction) needed to calculate the box scores."

It will be noted that the various criteria in the table are dependent on several distinct factors:

1) Human factors (1-2, 8, 9, 11)
2) Operational limits of combat systems (14-18, 1-2)
3) Operational limits of the vehicle (11-13)

Mandel states, "It is important to note that the actual values of slamming, propeller emergence, deck wetness, and sonar dome submergence criteria are all quite sensitive to the condition of loading and trim of the ship. Small, operationally feasible changes in trim may alter significantly the actual values of these criteria."

Under criterion no. 8, MSI denotes "Motion Sickness Index," as developed by O'Hanlon and McCauley (1973). It is defined as the percent of individuals who would vomit if subjected to vertical accelerations of specified amplitudes and frequencies. It appears to be a tentative and not entirely satisfactory criterion. See section on Habitability.

Quoting from Mandel (1979), "The PSEPR/ping (Criterion 17) is a payload-dictated criterion developed by Olson for the sonar search mission. Criterion 17 states that a certain number of excess ping returns are required for each ping sent out before sonar detection becomes possible.

Table 8
Seakeeping Criteria

(Lloyd and Andrew, 1977)

Author	Slamming	Motions	Deck Wetness	Propeller Emergence
Aertssen	3 or 4 slams(1) per 100 pitch oscillations.	Significant amplitude of acceleration at FP equals 0.4 g	"Green water"	25 emergences per 100 pitch oscillations.
Conolly	1 slam(2) at 0.2L abaft FP every 1360 seconds.	+ 1.0 g at 0.2L abaft FP every 673 seconds.	1 deck wetness at FP every 110 seconds.	-
Kehoe	1 slam(3)/minute at 0.15L abaft FP.	-	1 deck wetness FP every 60 seconds.	

(1) Slam defined as giving a maximum whipping stress of 5.9 MN/m^2 (in MV JORDAENS).

(2) Slam defined as having an impact velocity greater than $\left[\frac{20.8L}{kH}\right]^{1/2}$.

(3) Slam defined as having an impact velocity greater than $0.093 \left[\frac{g}{L}\right]^{1/2}$.

Aertssen's criteria are derived from analyses of full-scale trials (Aertssen, 1963, 1966, 1968, 1972) and as such represent actual limits on operation in the judgment of the ship's captain of the time. However, the measure of slamming is not related to physical realizations of slamming which are detectable by the captain and the motion criterion appears to be irrelevant to the actual environment experienced by the crew.

Conolly (1975) derived criteria by considering the performance of a destroyer which took part in comparative seakeeping trials described in Bledsoe, et al (1960). The slamming criterion includes a crude allowance for the effect of hull shape forward on slam severity but nevertheless is not related to sensations experienced by the captain. The motion criterion is subject to the same uncertainty as Aertssen's motion criterion.

Kehoe (1973) adopts Ochi's definition of slamming given in Ochi (1964). The resulting criterion takes no account of the effect of hull shape on the slamming characteristics of the ship and is not related to events detectable by the captain.

TABLE 9 - PRESCRIBED CRITERION VALUE SUBSTANTIATION FOR MONOHULL AND SWATH SEAKEEPING CRITERIA

Criterion			Page No. in Olson (1977)	Prescribed Criterion Value Substantiation	Criterion Category
No.	Symbol	Value			
1	ϕ	9.6 deg*	10	"...an average roll of 12-deg single amplitude was selected as a motion criterion reflecting consideration of personnel effectiveness." 12 deg/1.25 = 9.6-deg RMS roll.	Task Proficiency
2	θ	2.4 deg*	12	"A corresponding pitch criterion was chosen to be 3-deg average single amplitude pitch. While we found no specific pitch criterion based on consideration of human effectiveness, a 3-deg pitch is frequently cited as an operational limit on ship subsystems such as replenishment-at-sea equipment." 3 deg/1.25 = 2.4-deg RMS pitch.	Operational Limits of Vehicle Subsystems
8	MSI	20% after 2 hr exposure	D-3	"The developers of MSI found that...individuals who did not vomit within t_1 = 2 hours, rarely did during subsequent prolonged exposure." The 20 percent value is not substantiated.	Motion Sickness
9	$\ddot{z}$	0.2 g*	B-19	Aertssen '72 states that a commercial ship captain will slow down or alter course, if the significant vertical acceleration exceeds 0.4g at the bow; 0.4g/2 = 0.2 RMSg. (Bales '78 suggests a slightly higher value of 0.275 RMSg.)	Vehicle Structural Damage
11	N_s	1 per 2 to 5 min	8,9,16	Aertssen '72 states that a commercial ship captain will slow down or alter course, if a severe slam occurs more frequently than 3 times in 100 cycles. This is equivalent to 1 slam every 2 to 5 minutes. (Bales '78 suggests 4 times in 100 cycles.)	Vehicle Structural Damage
11	N_s	1 per 2 to 5 min	16	The 3350-ton SWATH was designed with an 18-ft clearance between the smooth water surface and the underdeck. Lamb '75 suggests that the 1/10-highest displacement of the relative motion between the SWATH and the waves also be limited to 18 ft; 18/2.55 = 7.1-ft RMS clearance. This is roughly the equivalent of one significant wave contact every 2 to 5 minutes.	Vehicle Structural Damage
12	Propeller Emergence		17	The 3350-ton SWATH was designed so that a relative vertical displacement of 12.8 ft between the smooth water surface and the propeller would expose 25 percent of the propeller radius in the vertical position. The maximum significant relative vertical displacement between the propeller and the waves was also taken as 12.8 ft; 12.8 ft/2 = 6.4-ft RMS displacement.	Operational Limit on Vehicle
13	N_s	1 per 2 min	9	"...it is suggested that ships rarely choose to take green water over the bow more than once every 2 to 5 minutes especially if gun mounts, missile launchers, or major deck equipment are located forward." One wetness every two minutes was selected by Olson '77 (Bales '78 suggests 4 deck wetnesses in 100 cycles.)	Vehicle Structural Damage; Possible Material Damage to Weapons Systems
14 15 16	ϕ z $\dot{z}$	3.2 deg* 2.1 ft* 3.5 ft/sec*	15 15 15	The values for these three criteria were stated by Baitis '75 The first is specified as 12.8-deg double amplitude significant roll; 12.8 deg/4 = 3.2-deg RMS roll. The second is specified as 8.34-ft double amplitude significant displacement; 8.34/4 = 2.1-ft RMS. The third is specified as 7-ft/sec significant vertical velocity of the flight deck; 7/2 = 3.5-ft/sec RMS velocity.	Helicopter Operation Limits
17	PSEPR/Ping	3-out-of-5	B-32	PSEPR/Ping of 3-out-of 5 is a commonly accepted sonar performance criterion according to Olson.	Sonar Search Operation Limits
18	t	30 sec	B-32	The value t = 30 seconds is based on a sonar search range of 10 miles.	Sonar Search Operation Limits

* rms of record

Mandel (1979)

In order to receive a ping return, the sonar dome must remain submerged during the time interval t between ping emission and ping return. This time interval of 30 seconds assigned to Criterion 18 in the table was selected by Olson on the basis of an assumed maximum sonar range of 10 miles. Olson applied Criteria 17 and 18 to monohulls but not to SWATHs because on SWATH the sonar dome is so deep that it never emerges."

"Olson included no weapons systems criteria because no reliable criteria for these functions have been developed. One of the important issues involved in weapon accuracy is that the flexural responses of the vehicle structure are important as well as the rigid body responses of the vehicle as a whole. Because of the complexity of the relation between gun and/or missile accuracy and ship motions, this topic has remained relatively unexplored until some recent work by Rockwell International (Hull, 1977) under NAVSEA and NAVSEC sponsorship. A joint NAVSEA-DTNSRDC-Rockwell project to explore this important issue further is planned."

Slightly different figures for the FF-1052 class are given by S. Bales, et al (1979):

No. 11 - 10 bottom slams/hr.

No. 13 - 60 wetnesses/hr = 1 wetness/min.

McMullen Associates (1976) found that some information was available for helicopter landings, based on actual trials in waves of 10.2 ft significant height. The accompanying Table 10 is an example of such data, including vertical and lateral accelerations as well as pitch and roll angles.

Criteria proposed by Lloyd and Andrew (1977), representing British Admiralty thinking at that date, are as follows:

a. Slamming

The whipping acceleration at the bridge should not exceed 0.05 g.

b. Wetness

The deck wetness interval should not be less than 100 seconds.

c. Motions

No definite criterion can be proposed but it is clear that subjective

Table 10. Levels of Ships Motion Under Which Helicopter Operation Difficulties Can Be Expected (McMullen Assoc., 1976)

Ship Motion	Motion Within Aircraft Event	Corresponding Sig. Motions
Pitch, Double Amplitude °	2.7 - 5.6	2.2 - 4.0
Roll, Double Amplitude °	6.4 - 14.6	4.4 - 11.1
Vertical Acceleration, g's	0.17 - 0.31	0.13 - 0.25
Lateral Acceleration, g's	0.12 - 0.20	0.09 - 0.16

NOTE: Above figures do not necessarily represent the highest levels of motion under which helicopter operations can be performed.

magnitudes* of 7 (JORDAENS) and 11 (Dutch destroyer) are tolerable. A tentative figure of 15 is suggested as a criterion.

d. Propeller Emergence

No definite criterion can be proposed but it is clear that an average interval of 40 seconds is tolerable (Jordaens). A tentative figure of 30 seconds is suggested as a criterion, but it is not clear whether such a limitation is actually required on geared turbine vessels.

The most complete statement of tentative figures for operational limits, or criteria, covering many different missions is that given by Johnson, et al (1979) and summarized in Table 11.

There is general agreement that insufficient data are available on actual acceptable values of the various criteria of seakeeping performance. But it is not always recognized that the precise numerical values selected

*"Subjective magnitude" above is an arbitrary scale of "intensity" of vertical sinusoidal motions, based on amplitude and frequency. It was derived from work by Schoenberger (1975) with USAF pilots.

TABLE II REQUIRED OPERATIONAL CAPABILITIES AND ASSOCIATED MOTION LIMITS

Mission Area	Required Operational Capability	Subsystem				Subsystem Motion Response Limits						
		Hull	Personnel	Equipment	Helo	Roll (Deg)	Pitch (Deg)	Deck Wetness (OCC/Hr)	Slamming (OCC/Hr)	Vert. Acc (g)	Latl. Acc (g)	Vert. Vel Ft/Sec
MOB	Replenishment	X				30	5	30	20			
	and Strike-		X			10	3			.4	.2	
	down			X		5	3					
	Day/Night*				X	6	3					6.5
MOB	Continuous	X				30	5	30	20			
	and efficient		X			10	3			.4	.2	
	OPS except			X		30	3					
	Repl & Helo											
MOB	Limited OPS	X				30	5	30	20			
			X			10	3			.4	.2	
				X		30	3					
MOB	Survivability	X				30	5	30	20			
			X			15	5			1.0	.5	
				X		30	3					
ASW SUW	Helo OPS	X				30	5	30	20			
			X			10	3			.4	.2	
				X		30	3					
					X	6	3					6.5
ASW	Sonar Dome	X				30	5	30	20			
	Detection		X			10	3			.4	.2	
				X		30						
AAW SUW	Deck-Mounted	X				30	5	30	20			
	Detection,		X			10	3					
	Tracking &			X		30	3			.4	.2	
	Weapons Firing											
	Systems											

Johnson, Caracostas and Comstock (1979)

for the criteria may have a profound effect on the attainable sea speed and mission effectiveness. For example, referring to the polar diagram, Fig. 5, it may be seen that in head seas a choice of 1 wet deck per minute (60/hr.) instead of 1 every 2 minutes (30/hr.) would make the difference between a limiting speed of 12.5 and 7.5 knots.

In this connection it is of interest to quote recommendations Nos. 8 and 9 of the Seakeeping Workshop (NAVSEA, 1975) to:

"Obtain data and develop design criteria relating to the sensitivity of personnel performance to the motion induced environment aboard a ship in a seaway."

"Obtain data and develop design criteria for the sensitivity of system and equipment performance to the motion induced environment aboard a ship in a seaway."

Also of interest is recommendation no. 12,

"Develop a meaningful dialogue between researcher, designer and operator.

"In determining priorities for future R&D efforts and improvement of ship design practices, it is necessary to address the real problems as seen by the fleet. Furthermore, information from experienced operators derived from a Fleet Seakeeping survey can be developed into design criteria for voluntary speed reduction, i.e., in-service data on acceptable slamming, deck wetness, rolling, etc. These criteria will then be integrated into the design process. Additional resources will be required to insure, by increased interaction between researcher, designer and operator, that evolving seakeeping technology will be satisfactorily applied to ship design."

This is an excellent statement, and perhaps requires only an addition regarding the need for simple instrumentation aboard ship. The purpose of such instruments would be to insure that "information from experienced operators" will be in quantitative rather than qualitative terms. The skipper should be able to quote numbers — such as accelerations at critical locations — to define the limit between being able to carry out any particular mission or not. Having such instrumentation on many ships, supplemented perhaps by a few more extensive manned installations to study several missions in greater detail, should provide us with much more complete, specific and reliable data on:

- Human factors
- Combat system limits
- Vehicle operational limits

In regard to human factors, it is doubtful that general studies (such as those discussed under the following section on Habitability) of human performance under different conditions of motions and accelerations can be of more than limited usefulness in determining performance limits for specific ships. The point is that the difficulties of various duties will vary greatly from one ship type to another and hence the effects of motions will be more or less serious. Furthermore, the duration of severe motions will have an effect on individual tolerance. Different ships may have characteristic responses to waves that differ greatly and may not be adequately described by conventional acceleration levels and frequencies. Some personnel may have become accustomed to ship motions — either long-term, indicating long experience at sea, or short-term, indicating that the ship has been at sea long enough for personnel to have their "sea legs". Hence, the availability of simple, permanent instrumentation is essential.

Similarly, the operational limits of combat systems and vehicles may vary so much among ships and missions that it appears to be essential to investigate limits of motions routinely at sea with the help of simple instrumentation, such as accelerometers. If these are located at selected positions that are critical for mission performance, then a correlation can be made between limits of motions (numerical values) and performance.

Another need for simple instrumentation accessible to the ship's officers is to enable them to determine when performance limits are reached under operating conditions at sea. This is discussed by Mandel (1979),

"In the current state of development, go, no-go (prescribed) values of the criteria (in the nature of highway speed limits) are employed. The basic assumption is that the Commanding Officer will be informed by instruments (like the automobile speedometer) of the actual value of all possibly constraining seakeeping responses and events. When the actual value of any single response exceeds the prescribed criterion value

assigned to that response, presumably the Commanding Officer will call for reducing speed and/or changing heading....In this respect, the prescribed value of a criterion is analogous to the posted speed limit on a highway, whereas the actual value of the criterion is analogous to the speed indicated by the speedometer of an automobile."

Every ship, therefore, should have an instrument — or instruments — that would be the "speedometer" for that ship. At the very least, a number of ships of every type should be so instrumented. An attempt will be made here to outline tentatively a possible minimum system, with the understanding that a further research and development project will be required. The first step is to identify the items to be monitored. Accelerations are known to be important, both for operation of equipment and for proper functioning of personnel. For most installations linear accelerations will probably suffice, oriented either for vertical or lateral components of motions. The bridge is an essential location, but other critical spots may be the location of sensitive instrumentation or the position of personnel engaged in motion-sensitive duties.

Strain gages can be provided to monitor either hull girder stresses or local stresses at critical locations. Or they can be installed on side frames at the bow, between weather deck and waterline to provide an indirect measure of relative bow motion and hence of the probability of shipping water.

For some purposes roll angle — either absolute or apparent — may be an important item to monitor. The instrument package must be flexible enough in design to be suitable for many different ship types and missions.

The next question is the type of readout or display to use, since a continually changing meter, for example, is difficult to observe and monitor. A good solution is to display the highest maximum value occurring over the previous 10 to 15 min., or alternatively, the rms value of the signal, obtained by averaging with a micro-processor continuously over the preceding 10 to 15-minute period. The first gives a direct indication of trends of extreme values, without sudden or frequent changes. The second must be used in connection with statistical factors (assuming a Rayleigh distribution) such as:

- "Significant" value (expected average of 1/3 highest) = 2 x rms
- Largest value expected in 100 cycles of motion = 3.25 x rms

It is urged that the development of such a flexible instrument package be given top priority in R&D planning.

Habitability

It is well to consider the general subject of habitability separately from the question of personnel performance of specific mission-oriented tasks. Quoting from McMullen Associates (1976), "The effectiveness of the crew is governed by two, or possibly three properties of motion:

1) linear and angular accelerations.
2) roll angle.
3) random variation of the plane in which the dominant angular motions are occurring, frequently called 'corkscrew motion.'

"Physiological response to the motions of a ship appear to be primarily a function of the induced linear acclerations. However, the response to the roll and pitch motions of the ship are also significant in determining the effectiveness of this important subsystem. Two aspects of human response must be considered in attempting to establish limiting levels of motion:

1) Motion sickness caused by linear and angular accelerations as well as corkscrew motion.
2) Degradation of motor performance caused by the rolling and pitching action of the ship. This can be further increased by fatigue resulting from continuous attempts to adjust to the ship's corkscrew motion....

"The state of knowledge of various environmental factors impacting on seakeeping, their current degree of investigation, and the degree of incorporation into the ship design process is shown in Table 12 (NAVSEA, 1975). Although motions in the range of 0.05 Hz to 10.0 Hz and the way they affect humans are of the most interest, they are the least well-described, as shown in Table 13, originally presented in NAVSEA (1975).

"Some effort has been expended in the development of data on the effects of motion and vibration in the 1.0 Hz to 10.0 Hz range. This

TABLE 12

STATUS OF ENVIRONMENTAL FACTORS IMPACTING SEAKEEPING AND MAN'S PERFORMANCE

Environmental Factors	State of Human Tolerance Data	Current R&D Support	Implementation in Ship Design	State-of-Art for Implementation
Motion/Vibration	Poor	Poor	Poor	Poor
Noise/Lighting	Good	Good	Fair	Good
Heat/Humidity	Fair	Fair	Fair	Good
Air Quality/ Ventilation	Fair	Fair	Poor	Fair
Work Safety	Fair	Poor	Poor	Good
Electromagnetic Radiation	Poor	Fair	Poor	Poor

TABLE 13

AVAILABILITY OF DATA RELATING SHIP MOTION EFFECTS TO MAN'S PERFORMANCE

Performance Interference:	Data Status:
1. Fatigue	1. None
2. Mechanical Interference	2. None except for current advanced ship work - not yet quantitative
3. Psychological	3. None
4. Bio-Medical	4. None except for limited sickness syndrome (see below)
5. Motion Sickness	5. Limited - data exists for the criteria of vomiting within two hours in young males, not seamen
6. Vibratory Motion	6. None applicable to ships - ISO standards not valid - wrong criteria (see below)
7. Motion in Other Than Vertical Plane	7. None

effort has primarily consisted of establishing narrow-band frequency responses to heave with a small amount of effort directed towards obtaining lateral plane data.

"Criteria for evaluation have been expressed mainly in terms of biodynamic effects and human tolerance. The standards that do exist in spectral range are both imprecise and of questionable validity for broad band exposure.

"Several investigations concerning motion effects in the 0.1 Hz to 1 Hz range have failed to cover the entire spectral range and have yielded such varying results that they have only confused things more.

"More recently, Human Factors Research, Inc., Goleta, California, under the sponsorhsip of the Office of Naval Research and the Bureau of Medicine and Surgery, has conducted research for the 0.1 to 0.5 Hz range for acclerations ranging from 0.0-0.5g's. Although these studies are promising, they have yet to produce useable quantitive data regarding long-term exposure, human adaptation, habituation, lateral accelerations and performance degradation."

Sample data are given in Figs. 11 and 12. Further research on personnel reactions to ship motions, vibrations, etc., is clearly needed.

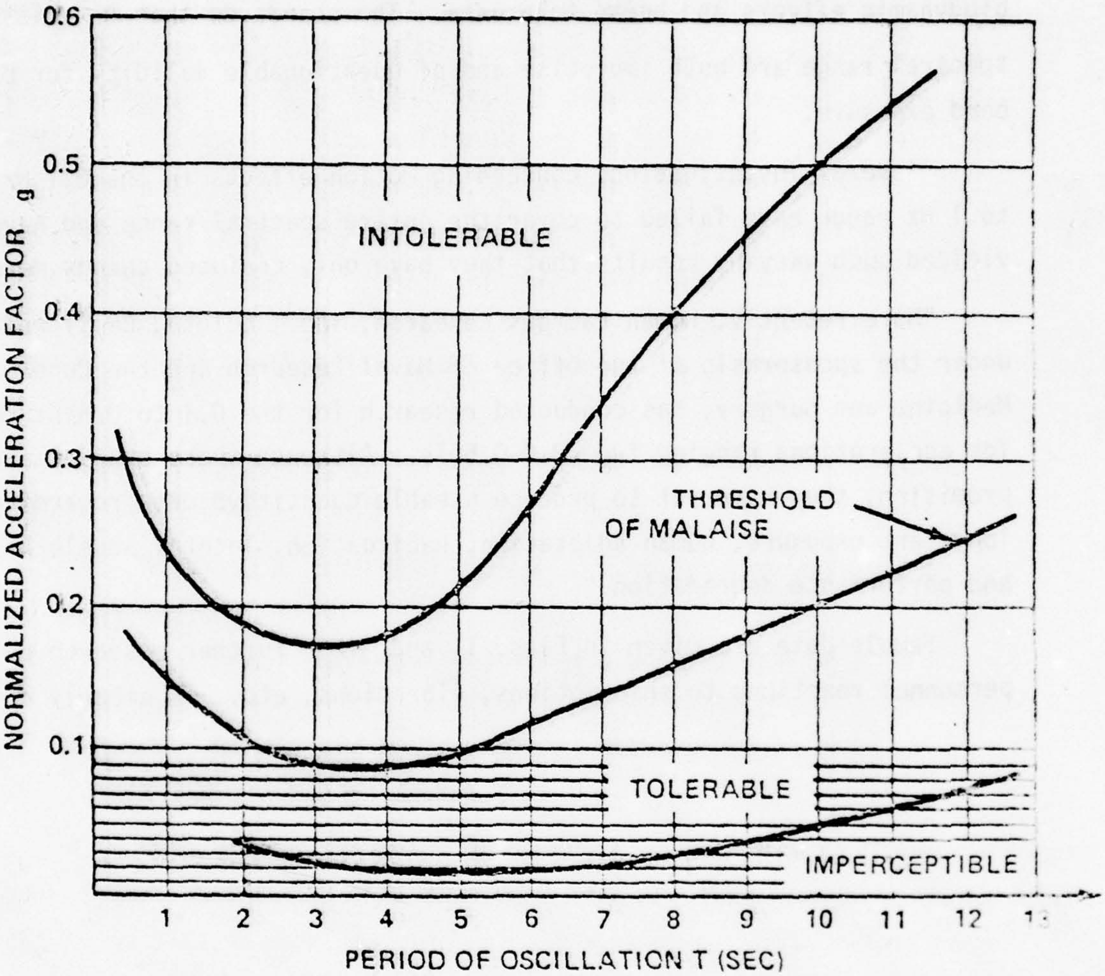


Figure 11. Human Tolerance to Vertical Acceleration, A Synthesis of Data Published up to 1969 (St. Denis, 1976).

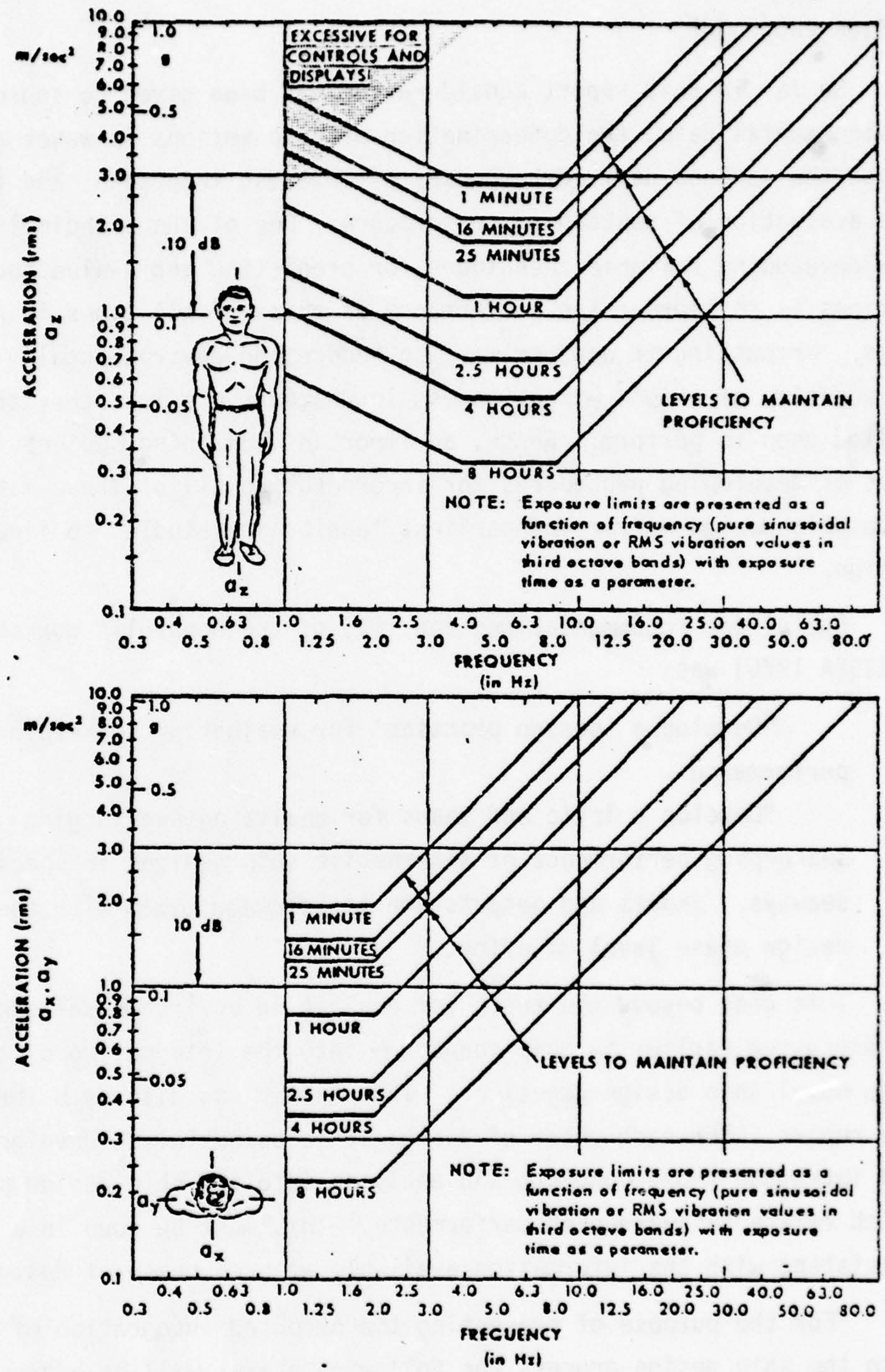


Figure 12. Vibration Exposure Criteria for Longitudinal (Upper Graph) and Transverse (Lower Graph) Directions with Respect to Body Axis (McMullen Associates 1976).

DESIGN PROCEDURES

So far in this report consideration has been given to sources of environmental data, the determination of ship motions in waves and hence the various derived responses of interest in design, and finally the evaluation of seakeeping performance. One of the principal reasons for developing reliable techniques for predicting and evaluating ship motions is to improve the performance of ships of all types in rough seas, or putting it another way, to reduce the environmental degradation of ship's effectiveness in whatever missions they are called upon to perform. Hence, an important remaining subject is that of developing procedures for incorporating all of these matters into ship design — from the earliest feasibility studies to final design.

One of the recommendations (no. 11) of the Annapolis Workshop (NAVSEA 1975) was:

> "Develop a 'design practice' for evaluating seakeeping performance.
>
> "Develop a logic and means for analyzing and judging seakeeping performance of alternative ship designs in specified seaways. Inputs and outputs are to be commensurate with the design phase level of effort."

This goes beyond the tools for evaluating environmental operability— as discussed earlier in this chapter — into the integration of these tools into naval ship design practice. This matter was discussed further in the report, "For each phase of design it is essential to develop, improve, and introduce those concepts and analyses into the ship design process which relate to seakeeping performance. This must be done in a manner consistent with the information available at each phase of design."

"For the purpose of presenting the proposed integration of seakeeping into the ship design process the following phases will be addressed:

1. Pre-Feasibility Study Phase
2. Feasibility Study Phase
3. Concept Design Phase
4. Preliminary Design Phase

5. Contract Design Phase

"For each phase a table is presented which contains the elements of the proposed integration and the supporting rationale." Because of the critical importance of the first two phases, the corresponding Tables 14 and 15 are included here. (Tables 3-1 and 3-2 of NAVSEA, 1975). The report concludes that, "The successful integration of seakeeping into the design process can be achieved only if it goes hand-in-hand with the development of more meaningful requirements and if funding support for the development of necessary data, tools and concepts is obtained."

Among the essential tools is one covered by recommendation no. 7,

> "Develop techniques for assessing seakeeping performance in the earliest design phases.:

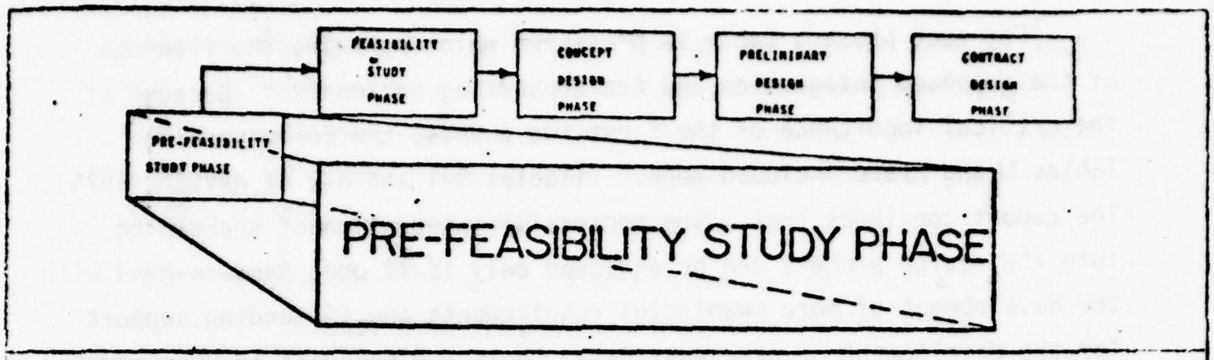
"If a ship is to be provided with good seakeeping qualities, it is essential that techniques be developed that will permit important choices of size, dimensions and form to be made on a rational basis in the very earliest design phases." Since the overall proportions of a ship have more influence on a ship's behavior than possible variations in hull form, it is important that the available techniques be applied at the very earliest stages of design — before details of hull form and weight distribution are known. A project to develop a simplified ship motion calculation procedure, involving Dr. M. St. Denis, L. T. Ravenscroft and J. F. O'Dea has been in progess at DTNSRDC for some time, and a report is expected in the near future.

The integration of seakeeping into design requires further research in other areas discussed elsewhere in this report. It also requires follow-up and verification in the fleet. Quoting recommendation no. 13 of the Annapolis Workshop (NAVSEA, 1975),

> "Develop a method for verifying predictions of seakeeping performance."

"Establish a follow-up quality assurance procedure for obtaining full scale inputs for evaluating seakeeping performance for (a) providing feedback to the designer and the operator and (b) improving and revising design criteria."

TABLE 14 SEAKEEPING IN SHIP DESIGN



A. Design Events and Decisions:

- **Operational Requirements are defined.**
- **Platform Type Selected: conventional monohull displacement type vs. one of the several alternatives (hydrofoil, SES, SWATH, multihull etc.)**
- **"Ballpark" size and cost established**

B. Implications for Seakeeping Performance:

- **Platform type and "ballpark" size has a first order effect on seakeeping behavior. Most unconventional platform configurations were developed in an attempt to improve seakeeping behavior.**

C. Seakeeping Analyses Required:

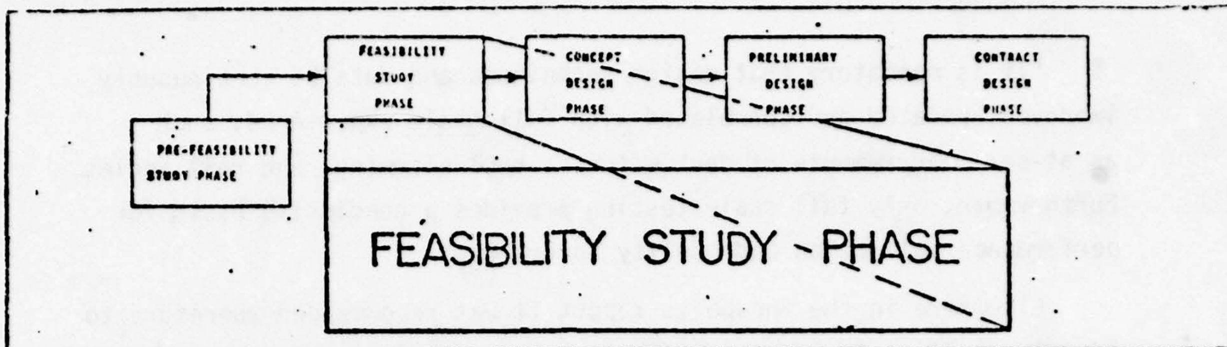
- **Studies of alternative force structures (numbers, sizes & types of platforms) must address relative seakeeping behavior (environmental operability).**

D. Prerequisites for Analyses: Status:*

- **Simple prediction tools to assess relative environmental operability, given primary mission and major payload items, for various platform sizes and types.** ⊗

*Legend: ○ Available; Must Be Improved. ⊗ Not Available; To Be Developed.

TABLE 15 SEAKEEPING IN SHIP DESIGN



A. <u>Design Events and Decisions:</u>

- Primary military payload and performance features (speed, endurance, protection, etc.)

B. <u>Implications for Seakeeping Performance:</u>

- Primary payload and performance features have the major effect on platform configuration and size and hence a dominant effect on seakeeping behavior.

C. <u>Seakeeping Analyses Required:</u>

- In studies of alternative payload and performance features, analyses are required to ensure that Operational Requirements can be satisfied.

D. <u>Prerequisites for Analyses:</u>

	<u>Status:*</u>
• Simplified prediction tools for use with existing ship synthesis computer models to predict: pertinent ship motions, speed limitations by power, slamming or wetness, etc.	⊗
• Improved freeboard criteria based on seakeeping considerations:	
-to weather deck for most ships	○
-to hangar deck for aircraft carrier types with deck edge elevators	○
• More appropriate environmental descriptors	⊗

*Legend: ○ Available; Must Be Improved. ⊗ Not Available; To Be Developed.

"It is mandatory that design techniques and data be continuously improved, updated and correlated with full scale experience, such as at-sea measurements of deck wetness, keel slamming, and roll angles. Furthermore, only full scale testing provides a conclusive basis for performance validation and quality assurance."

Elsewhere in the Annapolis report it was recommended therefore to "develop a Fleet Seakeeping Questionnaire and conduct selected seakeeping measurements to quantify present seakeeping performances and to verify improvements made." This is an obviously sound proposal and it is believed that the key to success lies in the words "measurements to quantify." Simple instrumentation available in many ships, as discussed in an earlier section, is essential to obtaining quantitative feedback from the Fleet.

Mention was also made in Chapter 3 of the need for "Seakeeping synthesis," establishing guidelines for the designer as to the influence of principal design parameters on seakeeping qualities. This subject was treated by Lewis (1967) (Sections 5.5 and 5.6 of Chapter IX) but needs to be expanded and brought up-to-date. Although papers have been written summarizing results of systematic computer calculations of ship motions (Bales and Cummins, 1970), they do not provide direct guidance to the designer. Design guidance is also needed regarding features such as acceptable bow freeboard.

APPLICATIONS TO SHIP OPERATION

Introduction

Developments in seakeeping have had relatively little application to ship operation. One important area for such application is in weather routing. This technique is being extensively used in the operation of both merchant and naval vessels (James, 1970), but the seakeeping inputs have been relatively crude — such as empirical curves of attainable speeds under different wave heights and ship headings. However, it is believed that better use could be made of available seakeeping tools, with the result that routing of ships would be significantly improved. The more accurately the effect of course and speed changes on ship responses can be calculated, the more precise can be the prediction of optimum routing in service.

An important development has been to provide guidance information to ship's officers to indicate the expected behavior of the ship in different sea conditions as a function of speed and heading. When motions become excessive — as indicated by slamming, shipping water, high accelerations, etc. — such information can be helpful in indicating the probable effect of different possible changes in speed or heading.

In many cases of merchant ships, such guidance information has been combined with the introduction of shipboard instrumentation to monitor

motions and stresses in order to warn the ship's officers of possible damage to the ship or its equipment. (Hoffman and Lewis, 1975; Hoffman, 1976).

Shipboard instrumentation is also of long-term value in providing numerical yardsticks to establish with greater precision acceptable limits of motions for design. This is discussed in preceding sections of this chapter.

Weather Routing

For weather routing, as well as for shipboard guidance, there are two basic considerations:

- Involuntary speed reduction because of added power requirements.
- Voluntary speed reduction, and/or course changes, to avoid adverse effects of ship motions.

In both cases it is important to consider the effects of changes in ship heading, as well as in draft and trim.

Reference to a figure of Aertssen (1972) (Fig. 13) is helpful in visualizing what must be predicted to satisfy the above needs. First is a prediction of SHP vs. speed for various headings in different sea conditions, and second is a prediction of acceptable voluntary limits on speed, also for various headings and sea conditions. For estimation of fuel consumption the prediction of RPM would also be helpful. The prediction of SHP requires consideration of added resistance in waves (including both reflection effects and motions), effects of waves and ship motion on propulsive efficiency and the performance characteristics of the propulsion machinery. For example, at constant throttle settings a diesel plant tends to develop constant torque, while a geared turbine plant delivers constant power. See section on Powering in Waves.

Voluntary speed reduction or change of course in rough seas is generally related to one or more of the following:

- Shipping water.
- Slamming (on bottom or flare).
- Propeller emergence.
- High vertical, lateral or angular accelerations.
- Absolute (or apparent) roll angle.

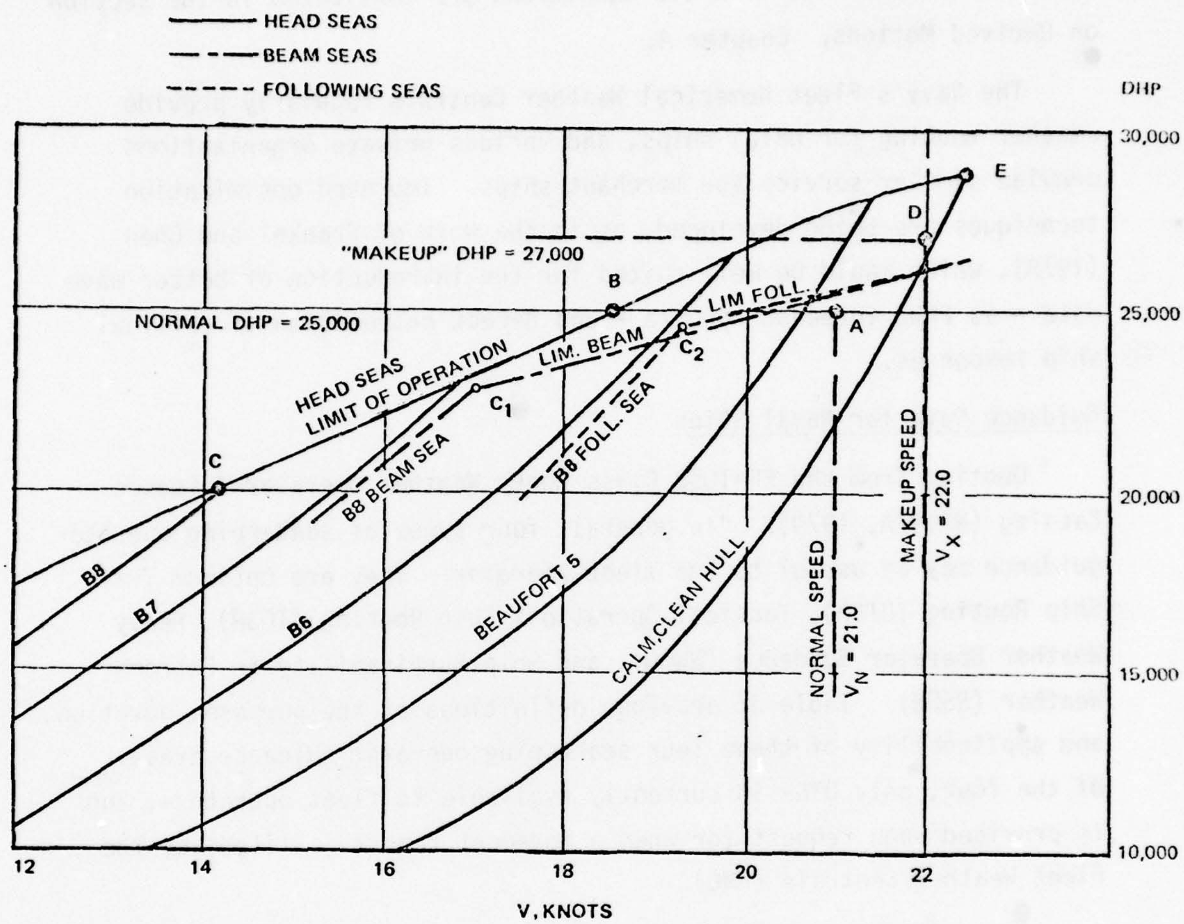


Figure 13. Service Performance of Dart Europe in Full Load Condition (Aertssen and van Sluys, 1972)

Acceptable limits to the above are discussed in the section on Numerical Data on Criteria of Seakeeping Performance, and means of predicting values for specific ships in specific sea conditions are considered in the section on Derived Motions, Chapter 4.

The Navy's Fleet Numerical Weather Centrals regularly provide weather routing for naval ships, and various private organizations provide similar service for merchant ships. Improved optimization techniques are being developed, as in the work of Frankel and Chen (1978), which would be well suited for the introduction of better wave data — as FNWC forecast spectra — and direct calculation of critical ship responses.

Guidance Data for Naval Ships

Quoting from the FF-1052 Class Heavy Weather Operator Guidance Catalog (NAVSEA, 1979). "In general, four types of seakeeping operator guidance may be useful to the fleet operator. They are Optimum Track Ship Routing (OTSR), Tactical Operations Ship Routing (TOSR), Heavy Weather Operator Guidance (HWOG), and Ship Survivability in Extreme Weather (SSEW). Table 16 provides definitions of the purpose, duration, and applicability of these four seakeeping operator guidance areas. Of the four, only OTSR is currently available to fleet operators, and is provided upon request (or when a movement report is filed) by the Fleet Weather Centrals (FWC).

Bales (1976) discusses OTSR and non-Navy weather routing services, and summarizes possible improvements that can be made through,

- Better ocean wave forecasting
- Utilizing available ship motion computer programs in evaluating ship responses.

HWOG will be considered here, but TOSR and SSEW will be deferred.

Bales, et al (1979) have discussed the problem of providing heavy weather operator guidance information to ships of the fleet. Three possible procedures are described:

1) Prepare a catalog of data on critical ship responses to different sea conditions, on the basis of shore-based computer calculations, and distribute to ships for reference.

TABLE 16 TYPES OF SEAKEEPING OPERATOR GUIDANCE

Type	Purpose	Duration	Applicable Sea Conditions
Optimum Track Ship Routing (OTSR)	Minimize transit time or fuel consumption	Long-term (10 days or less), e.g. transit route	Avoid heights in excess of given limit, e.g., significant wave height of 12 feet
Tactical Operations Ship Routing (TOSR)	Minimize ship motions in order to conduct an operation	Short-term, e.g. local area	Significant wave heights of 20 feet or less
Heavy Weather Operator Guidance (HWOG)	Minimize ship motions in order to avoid damage	Short-term, e.g. local area	Significant wave heights between 10 and 40 feet
Ship Survivability in Extreme Weather (SSEW)	Avoid broaching, capsizing, or major structural failure	Short-term, e.g. local area	Significant wave heights in excess of 40 feet

NAVSEA (1979)

2) Transmit shore-based forecast data on local seaways (in spectral form) to ships and utilize shipboard computer facilities to calculate predicted ship responses.

3) Make use of shipboard wave measurements as input to shipboard computed ship responses.

The last of these procedures cannot be implemented until shipboard (or ship deployed) instrumentation now under development becomes reliable and fully operational. The second is presently feasible and is being evaluated as part of an instrumentation study on the USNS Furman (S. Bales, 1976). It requires the availability of suitable onboard computer hardware and software, as well as reliable and fast ship-to-shore communication (by satellite). This will be discussed further under Shipboard Instrumentation.

The simplest approach is the first of the above, since it involves the pre-calculation of guidance data on shore. Bales, et al (1979) describe a pilot project for the FF-1052 class vessels, in which a Heavy Weather Operator Guidance (HWOG) Catalog has been distributed on a trial basis to Fleet Commanders by Navsea (1979). Details are given by Bales and Foley (1979).

Quoting from Navsea (1979), "The purpose of the Catalog is to provide the operator with quantitative information as to how the ship responds in a seaway and some guidance for avoiding excessive ship motions or related events such as slamming and wetness, during heavy weather conditions, that may cause damage to the ship. The Catalog makes no attempt to tell the operator what to do, but rather describes what he may expect under a set of arbitrary sea conditions....

"In brief, the HWOG Catalog consists of graphs which indicate the ship heading and speed combinations, for a variety of sea conditions, that may cause excessive ship motions or related events, and hence damage to the ship or some loss of mission effectiveness, combat readiness, or crew safety may be experienced. As well, the Catalog indicates heading and speed combinations which may minimize ship motions. The criteria used for identifying ship damage potential were developed primarily from an examination of Casualty Reports for the ship class." (Lain and Guilfoyle, 1977).

Quoting from Bales, et al (1979), Figure 14,"provides a sample graph from the Catalog, illustrating the operating envelope, as a function of ship speed and ship heading, provided as guidance for avoiding shipboard damage due to the encountered .... seaway. In this case, the seaway is characterized by a significant wave height of 20 feet, a peak (or modal) period of 9 seconds, and is considered long-crested or uni-directional. The concentric circles on the graph represent ship speeds and the radial lines indicate ship headings to the seaway. The more boldly shaded areas (larger dots) illustrate operating regions (heading and speed combinations), in which damage will probably occur about 95 percent of the time. The more lightly shaded areas (smaller dots) represent operating regions in which damage will occur about 5 percent of the time. By judiciously applying this intelligence data, the ship operator can potentially improve his probability of avoiding heavy weather damage to his ship."

Criteria used in arriving at the operating envelope were as follows:

FF-1052 CLASS MOTION OR EVENT LIMITS TO AVOID DAMAGE

Response or Event	Probable Limit	Possible Limit	Impact
Roll Angle (RMS, Degrees)*	10	5	Personnel/Sensors on Mast
Pitch Angle (RMS, Degrees)*	3	1.5	Personnel/Sensors on Mast
Bottom Slams (No. Per Hour at Frame 25)	10	1	Mack/Mast/Sensors on Mast
Bow Wetness (No. Per Hour)	60	30	5" Gun Shield/ASROC/House Front
Stern Wetness (No. Per Hour)	3	1	IVDS Machinery (No Doors or Poorly Fitted)

*Note: RMS Angles are given. These values correspond to standard deviations of ship motion which are about one-half the "significant" values observed in a heavy seaway.

The catalog also contains speed-polar "data base" graphs showing contours of ship motions, on which the operating envelopes are based (Fig.15).

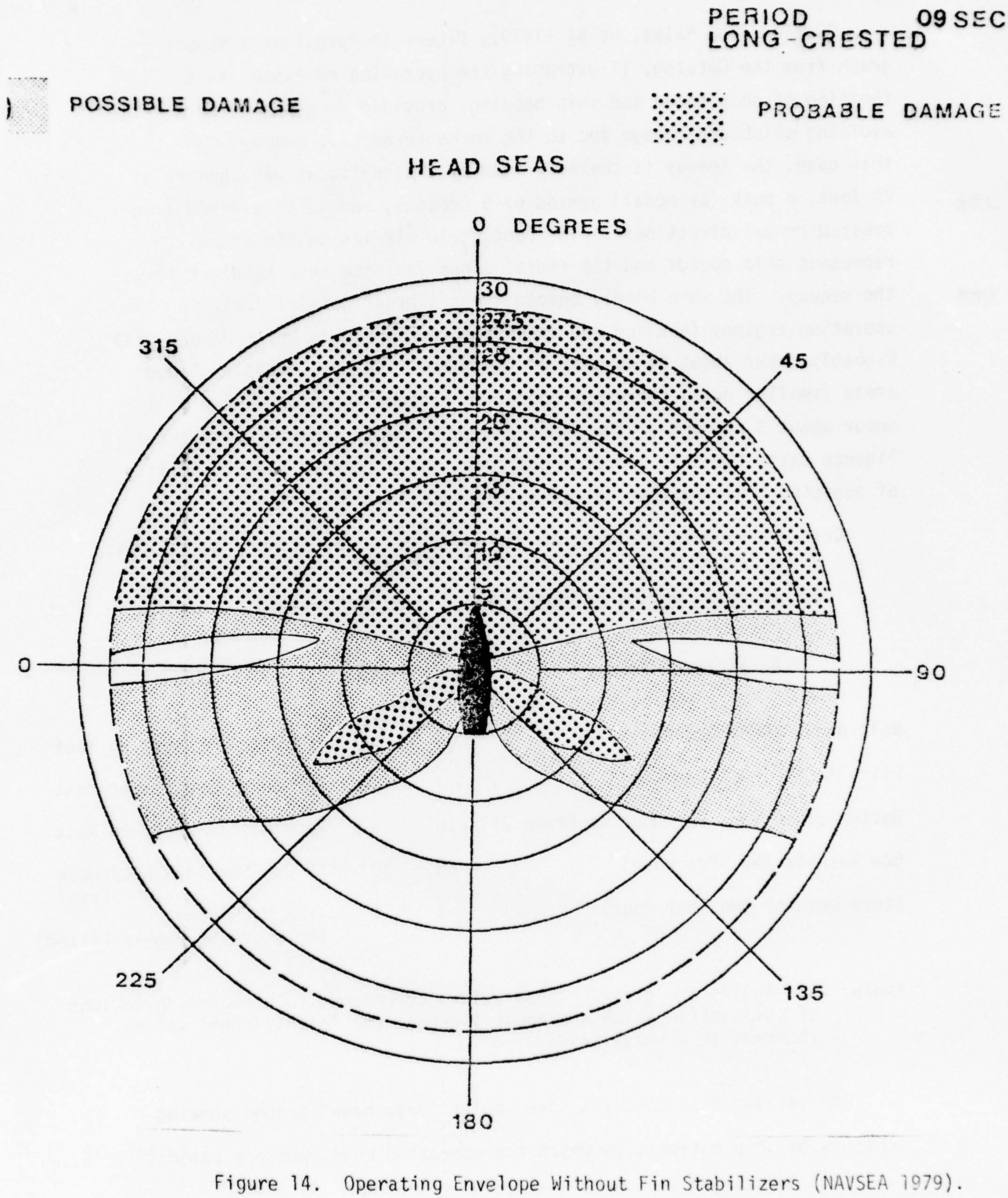


Figure 14. Operating Envelope Without Fin Stabilizers (NAVSEA 1979).

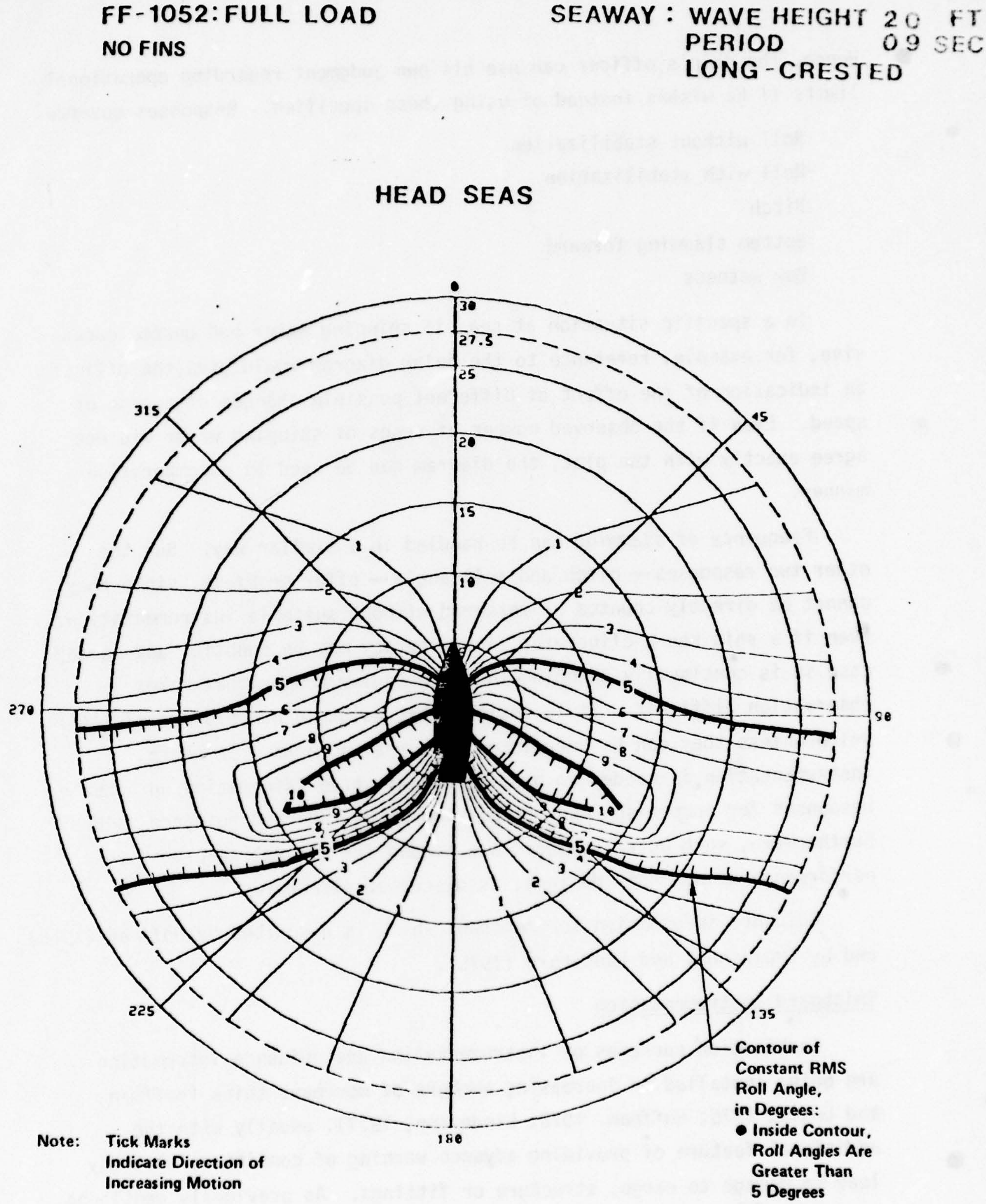


Figure 15. Typical Speed Polar Graph Containing Ship Motion Contours (NAVSEA 1979).

Hence, the ship's officer can use his own judgment regarding operational limits if he wishes instead of using those specified. Responses covered:

Roll without stabilization
Roll with stabilization
Pitch
Bottom slamming forward
Bow wetness

In a specific situation at sea, if shipping water had become excessive, for example, reference to the polar diagram would give the officer an indication of the effect of different possible changes of course or speed. Even if the observed number of cases of shipping water did not agree exactly with the plot, the diagram can be used in a comparative manner.

Frequency of slamming can be handled in a similar way. But the other two responses — pitch and roll angle — offer problems, since they cannot be directly counted or measured without suitable instrumentation. Even if a ship has a clinometer, its accuracy may be doubtful and in any case it is continually changing in an irregular manner that makes observation difficult. It is obsious that guidance numbers are of little value unless they can be correlated with real numbers. In short, instrumentation is needed to provide quantitative information on actual responses for comparison and correlation with predicted guidance values. Furthermore, such actual numbers are needed for evaluating predicted performance of new ship designs, as discussed elsewhere.

Guidance information for merchant ships is described by Hoffman (1976) and by Cruikshank and Landsburg (1975).

Shipboard Instrumentation

Combination packages of instrumentation and guidance information are being installed on increasing numbers of merchant ships (Hoffman and Lewis, 1975; Hoffman, 1976; Lindemann, 1977), usually with the additional feature of providing advance warning of conditions that may lead to damage to cargo, structure or fittings. As previously mentioned, a trial installation is being made on the U.S.N.S. Furman, which is a modified Victory ship in North Pacific service (S. Bales, 1976). This instrumentation is similar to those previously installed on merchant

ships (Hoffman, 1976), and incorporates a mini-computer to permit calculation of predicted responses to forecast wave spectra (from FNWC) and to provide more flexible guidance information than can be provided in pre-calculated Guidance Catalogs.

Results of the above trial installation will be of value in planning for possible warning and guidance instrumentation that might be suitable for naval vessels generally. In developing such a naval system the primary objective would be to provide warning of possible ship responses that might lead to injury to personnel or damage to the ship's hull, equipment or fittings. It would also provide assistance in judging whether or not specific missions could be carried out and would be coordinated with guidance information supplied to the ship's officers.

Hence, the exact ideal format for the polar diagrams, or other form of presentation of guidance data, should be considered for optimum coordination with instrumentation. Or if a mini-computer is incorporated into the warning system, the guidance information can be included in the computer software and displayed on a bridge-mounted cathode ray tube, as in the Great Lakes system described in a recent report (Center for Maritime Studies, 1979).

It should be noted that the above proposed operational warning and guidance system would of necessity be more complex than the minimum system discussed under Numerical Data on Criteria of Seakeeping Performance.

Conclusions

Better mission performance of naval vessels in rough seas can be expected if optimum use is made of seakeeping knowledge in weather routing procedures. Furthermore, the combination of simple shipboard instrumentation and seakeeping guidance data should accomplish one of the important recommendations of the Annapolis Workshop (NAVSEA, 1975) to "develop a meaningful dialogue between researcher, designer and operator." A research project is needed to determine the specficiation for an optimum instrumentation package for naval ships.

SURVIVABILITY

Introduction

An important aspect of seakeeping in general is that of survivability. This is the ultimate requirement of an acceptable ship design; whether or not the ship can effectively carry out its mission under any severe sea condition, it should at least be able to "live to fight (the sea) another day." Some environmental threats to survivability to be considered are:

- Hull structural failure
- Capsizing, with or without broaching

It is of interest to quote recommendation no. 14 (a) from the Annapolis Workshop (Navsea, 1975).

> "Conduct research directed at platform survival in extreme environmental conditions.

"Ship acquisition cost constraints and the trend toward increasingly refined ship design are reducing platform survivability margins. Research is required on platform survival in extreme environmental conditions to prevent the reduction of these margins below safe limits. The platform survivability aspects of control in following/quartering seas (broaching), intact stability (capsizing), and extreme structural loadings (hull girder and local failures) should be clearly understood."

Since in general these phenomena involve very severe sea conditions, and correspondingly large amplitudes of motion outside the linear range, the choice of the best theoretical and/or experimental approaches must be carefully considered.

Structural Failure

Considering first the hazard of possible hull structural failure, a promising approach that is making steady progress under the aegis of classification societies and the ISSC is to predict short-term trends of bending moments under different sea conditions and then to integrate over all possible conditions to obtain the highest expected moment in the lifetime of a ship, or of many ships. It turns out that the governing bending moment value for design is not that due to the highest

possible sea — since its occurence is very, very rare — but a sea condition somewhat less severe that is more probable. Furthermore, Dalzell (1963) showed by model tests that midship were bending moments were nearly linear with wave height up to surprisingly severe conditions. In fact, very steep regular laboratory waves produced much higher bending moments than the most pessimistic predictions for real ocean conditions. However, the bending moments in steep waves were somewhat lower in relation to wave height. Hence, it seems likely that the use of the basically linear techniques for predicting wave-induced bending moments (discussed in more detail in the section on Wave Loads) are acceptable and not overly safe methods. Model tests remain invaluable as a means of checking various theoretical methods, particularly when applied to new or unusual designs.

A completely rational answer to the problem of hull structural failure requires the further development of the reliability approach to design, whereby both demand (loads) and capability (strength) are expressed in probabilistic terms and an estimate of failure probability results. Such an approach can replace the conventional method in which a design load is related to nominal strength by means of an empirical factor of safety. Some work has already been done in the reliability approach to ship structural design — based on the original work of Freudenthal (1947) — such as Mansour and Faulkner (1972), Lewis (1976), Stiansen, et al (1979), and Ang (1979). A great deal more research needs to be done on the problem, particularly on the probabilistic aspects of capability, and the subject is being given increasing attention by the International Ship Structures Congress. Meanwhile, it is believed that the so-called semi-probabilistic methods offer little improvement over the conventional approach, since a factor of safety is still required.

Capsizing

The threat of capsizing is a hazard that obviously is associated with severe wave conditions and hence non-linear responses. Hence, experimental studies have been essential to obtaining an understanding of the phenomena involved. But a parallel theoretical approach is also

imperative, and the problem is to select only essential features of non-linear theory, perhaps following a time-domain solution rather than one in the frequency domain.

The valuable pioneering work of Paulling and Wood (1974) under Coast Guard sponsorship showed for high-speed cargo ships that "capsizing is most likely to occur at high speed in following or quartering seas when the ship motion is dominated by hydrostatic forces. A time-domain numerical simulation of the motion and capsizing is developed and coded for machine computation, taking advantage of the hydrostatic dominance noted above." Hence, although the theory requires further development and checking against experiment, it is clear that non-linearities can be accounted for without requiring a complete dynamic, non-linear theory. This should provide a sound basis for establishing stability standards and designing safe ships. See section on Control in Waves.

The overall status of research on capsizing was thoroughly reviewed by Barr (1977). This survey covers the Proceedings of the International Symposium on Stability of Ships and Ocean Vehicles held in Glasgow in 1975 and recent studies supported by the U. S. Coast Guard on the following:

- Small recreational boats
- Towing and fishing boats
- Container and break-bulk cargo ships

Not mentioned is a paper by Nicholson (1974) that deals with experimental studies on a warship form.

The ultimate objective of all this work is the establishment of rational stability criteria for all types of ships. Barr concludes that poor correlation between full-scale behavior and either model tests or theory suggests the need for considerable more work in the recreational boat problem. However, theory and experiment have together resulted in excellent progress for towing and fishing vessels (Amy, et al, 1976) and for modern cargo ships (Paulling and Wood, 1974). The same may be said for naval types (Nicholson, 1975) using free-running models in a large, rectangular basin.

Paulling's experiments with a self-propelled, radio-controlled model in San Francisco Bay have shown three distinct modes of capsizing, all

involving high speed in quartering and following seas, with stability reduction when a wave crest is amidships:

- Low-cycle resonance, an oscillatory rolling that builds up rapidly in a few cycles.
- Pure loss of stability, resulting from a long, high wave travelling at almost the same speed as the ship.
- Broaching, resulting from 3 or 4 successive steep, breaking waves.

Thus, available research results provide useful design guidance, and powerful experimental techniques for investigating unusual cases are available. There are few tanks in operation for testing in oblique waves, and none yet in a position to create short-crested seas. For greater realism in model tank tests, at least a few capable of generating realistic short-crested seas would be of value. It is reported (Murdey, 1979) that a new short-crested wave facility is going into operation at the University of Edinburgh and such capabilities are planned for the new seakeeping basin at Trondheim and at the Arctic Vessel and Marine Research Institute in St. John's, Newfoundland. Meanwhile, work should continue on quasi-static, non-linear theoretical methods of evaluating a ship's ability to resist capsizing.

Chapter 5

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Chapter 6

HIGH PRIORITY RESEARCH NEEDS

INTRODUCTION

Throughout the survey of seakeeping research, as presented in Chapters 2-5, numerous gaps in our knowledge have been noted and suggestions for further research made. Most of these research needs are already well known, and many will be addressed in the normal course of ongoing research. Hence, the emphasis here is on high priority projects, research that is urgently needed to accelerate progress toward the goal of effectively applying seakeeping principles to the design of more efficient ships.

The author believes that in engineering fields there is a place for both free, unfettered research in the scientific spirit, directed only toward increased knowledge and understanding of physical phenomena, and for directed research aimed at the practical solution of specific engineering problems. It is the latter which will be given particular attention in this chapter.

The sections giving brief descriptions of first priority projects in different areas will be followed by a section summarizing other important subjects for research believed to be somewhat less urgent and therefore designated second priority.

ENVIRONMENT

1. Verification of Hindcast Techniques (pp. 13-15). (See Workshop Rec. 10).

The best potential source of systematic worldwide data on ocean waves in spectral form for use of ships designers appears to be wave hindcast techniques, such as those in operation at the Fleet Numerical Weather Central, Monterey. However, the value of such data depends on both the validity of the hindcast methodology and the accuracy of the wind field observations utilized.

Hence, it is essential that extensive, routine verification of hindcast procedures be carried out. This can be done on the basis of:

- Direct one-to-one comparisons of wave spectra obtained from wave measurements with hindcast spectra for the same location and time.

- Statistical comparisons of histograms of wave heights and periods obtained by observations and from hindcasts. Reference: Hoffman and Walden (1977).

2. Wave Measurements (pp. 13 and 16).

There is a continuing need for ocean wave data obtained from direct measurements on ocean shipping routes. This need is twofold:

- To provide a basis for verifying hindcast techniques applied to the open ocean as discussed above.
- To provide direct information on waves in locations of unusual sea severity, as in shoaling water (on a continental shelf) or where there are strong current effects.

Shipborne wave recorders on weather ships are ideal for the first purpose; moored buoys are suitable for the second. The following tentative buoy locations were suggested by Hoffman and Walden (1977):

a) North Atlantic (Grand Banks, Faraday Sea Mount).
b) Near entrance to English Channel.
c) North Pacific (south of Aleutians).
d) Off coast of South Africa.

It is believed that those concerned with the design and worldwide operation of naval and merchant ships must take the initiative here, rather than to wait for others to supply the data.

SHIP MOTIONS

3. Simplified Procedures (p. 123) (Workshop Rec. 7).

A distinction has been made in this report between the prediction of ships motions (pitch, heave, roll, yaw, sway) and of derived responses (local acceleration, deck wetness, slamming, added resistance, wave loads, etc.) The amplitudes of the former, and to some extent the latter, depend greatly on basic ship characteristics that are usually established at the earliest stages of design. Unless the effects of adopting alternative ship characteristics can be assessed at these early stages, the possibility of optimizing the design in relation to seakeeping performance must be ruled out.

Hence, a computer calculation procedure for basic ship motions (RAOs) should be developed for use in early pre-feasibility and feasibility studies before details of hull form and weight distribution have been

established. It should be simplified for economy in routine use, but should be capable of accurately evaluating the effects of changes in:

- Ship dimensions.
- Displacement.
- Weight distribution.
- LCB and LCF (transom width).
- Type of sections (U or V).

Work is now in progress at DTNSRDC (Dr. J. F. O'Dea) on a project in this area, but its priority is not high.

References: Korvin-Kroukovsky (1957
Lewis (1967) (Chapter IX of PNA)

4. Non-linear Theory. (pp. 34, 43, 69-73)

Selective applications of non-linear approaches to ship motion theory are needed in order to obtain better practical solutions to problems such as shipping water, slamming, control of motions and added resistance) — as discussed subsequently. This need arises mainly from the non-linear effects associated with above-water hull shape, low frequencies of encounter (following and quartering seas), and absence of restoring forces in sway, surge and yaw.

Hence, further theoretical work is needed along lines such as:

- Non-linear restoring forces (Salvesen, 1974, 1978).
- Incorporating rudder effects into the equations of motion (Eda, 1978).
- Introducing additional coupling terms, such as pitch-yaw (Korvin-Kroukovsky, 1961).
- Allowing for transverse stability effects (Paulling, 1974).
- Forward speed effects, especially in quartering and following seas.

Experimental verification of developments in the above areas is also needed.

DERIVED RESPONSES

5. Shipping Water (pp. 41-44; 57-58).

Combined theoretical and experimental research is needed to develop improved methods of predicting:

- Wave refraction effects as a result of bow motions, including influence of above-water hull form (flare).
- Magnitude and duration of vertical component of hydrodynamic pressure on above-water hull (flare) at water entry.

It is assumed that static bow wave build-up resulting from ship's forward motion is already fairly well understood.

Theoretical work would involve the introduction of suitable non-linear terms, following Kaplan (1972), Chapman (1979), and Salvesen (1978). (See Item 4 above). A project entitled, "Advanced method for ship-motion and wave-load predictions," emphasizing the effect of above water hull form on motions and loads, is included in the Ship Structure Committee program for Fiscal 1980.

Experimental work should be directed toward checking theoretical developments and should therefore include measurements of relative bow motions, shipping water and local pressures on flare. An early series of systematic tests with varying above-water form would also provide interim empirical data for design use pending the development of suitable, confirmed theory. And irregular wave test techniques should be refined and applied for routine evaluation of design alternatives.

References: van Sluijs (1972)
Chiocco and Numata (1969)(CONF)
Bales (1978)

6. Slamming (pp. 44-45; 54-57).

Although the basic rationale for predicting the occurrence of bottom slamming and estimating magnitude and duration of local pressures has been developed by Ochi/Motter (1973) and Stavovy/Chuang (1976) and given interim application by Schmitke (1979), there are a number of important gaps to be filled.

First a survey is needed of available experimental and theoretical data to attempt to clarify the effect of section shape (near the bottom and in the area of impact) on the critical relative vertical velocity. This survey should lead to some recommendations for further experimental research.

Second, theoretical and experimental work along the line of Beukelman (1979) should be pursued to clarify the combined effect on pressures of forward speed and angle between keel and wave slope at impact. This work should include the estimation of duration and distribution of impact pressures, with experimental verification.

Third, the above considerations should be incorporated into the procedure for estimating probability of slamming in irregular seas. The early work of Tick (1958) on slamming probability took account of angle of impact but apparently was incorrect in assuming that maximum pressures occur at zero angle and did not allow for forward speed.

Finally, the above work should be extended as necessary and applied to the problem of impact on sponsons and other appendages. Meanwhile, irregular wave test techniques should be refined and applied for routine evaluation of design alternatives.

7. Control of Motions (pp. 68-76)

Obtaining a better understanding of ship motions in following and quartering seas, as proposed in Item 4 above, should make it possible to improve the design of high-speed ships for better course-keeping and control of rolling. One of the big problems is that of yaw-roll coupling, but the need is not simply for means of reducing the effect of steering on roll (or heel) but to coordinate steering with control of roll. An alternate bold approach is to use the rudder to reduce rolling (A. E. Baitis is working on this at DTNSRDC). The goal is to be able to design hull, appendages, rudder, steering gear and automatic control system to achieve:

- Automatic steering in severe following and quartering seas that is superior to manual steering.
- Elimination of yaw-heel effects and significant reduction of roll as well.

The achievement of the above goals will require a systems approach to the overall evaluation of ship control, making use of advances in hydrodynamic theory previously described, coupled with control theory principles. Experimental support and verification (van Hooff, 1975; Paulling, 1974) is also needed. Full-scale measurements are required, both for assisting in the understanding of the problem and providing verification of theory (Taggart, 1970).

In order to apply the above new developments to improved design it is also necessary to establish standards of acceptable course-keeping performance, as discussed in the next section.

8. <u>Shipboard Instrumentation</u> (pp. 114-117) (See Workshop Recs. 12 & 13)

One of the most urgent problems in seakeeping is the determination of more reliable numerical values of criteria of performance, e.g. limiting magnitudes of angular motions or of accelerations at critical locations, frequency of shipping water and slamming, etc. Such refinement in numerical criteria cannot be attained without the installation of simple instruments on many ships of all types.

Hence, a simple instrumentation package should be developed for mass production and ready installation on all types of naval vessels. Its main purpose would be to display numerical values of important ship responses for correlation with degree of success in carrying out various missions under rough sea conditions. The data would be displayed in the form of short-term averages (or extreme values in a stated period), so that displays are not rapidly changing.

The project should begin with a study of specific sensors to be included, such as:

- Local accelerations (vertical or transverse).
- Strain gages at critical points from viewpoint of structural loadings.
- Roll angle (true or apparent).
- Strain gages (or pressure gages) at sides of bow to measure relative bow motion (related to deck wetness).

Of course, the actual choice of sensors and their locations would vary with ship type and mission.

After determining a suitable form of display, a standard package should be designed and a trial installation made for evaluation on a representative ship.

The development of a suitable instrument package should be followed by installation on a variety of types of ships. However, it is not intended that extensive data collections and analysis should be undertaken. Rather all deck officers should be requested to keep their own notes on correlation between mission performance and instrument readings. Hence, questionnaires to or dialogs with fleet operating personnel — as called for in the Annapolis Workshop and in the following section on second priority research — can be based on quantitative data.

9. Combatant capability assessment (CCA) (pp. 99-100)

CCA techniques offer the potential of evaluating the influence of many factors — the ship, its equipment, personnel performance and the environment — on performance of combat systems. Hence, they should make it possible to determine the typical influence of seakeeping on combatant capability and to clarify the relative importance of different responses as seakeeping criteria, as well as perhaps to reveal some new, overlooked criterion.

Hence, trial applications of CCA techniques should be made to determine the degradation of performance of several specific ships in rough seas when engaged in specific missions, such as:

- ASW.
- Missile launching.

By assuming different sea states, ship speeds and headings, trends could be determined between mission performance and critical ship responses, such as:

- Accelerations
- Angles of roll
- Hull deflection
- Course keeping

In some cases actual numerical values of performance criteria might be obtained. Direct evaluation could also be made of such measures as the addition of anti-rolling fins, for example.

Reference: Prout (1974)

10. Evaluation Procedures (pp. 88-99) (Workshop Rec. 14b).

An essential aspect of applying seakeeping knowledges to ship design is the development and refinement of procedures for evaluating seakeeping performance (environmental operability). Various procedures have been proposed and developed, but none have been generally agreed upon and accepted. In general, these procedures attempt to evaluate over a period of time,

$$\frac{\text{Mission effectiveness in rough seas}}{\text{Mission effectiveness in calm seas.}}$$

In some cases, such as sonar search, aircraft carrier operation, and surface warfare it is difficult to simplify the problem. However, in some cases the evaluation can be reduced to a comparison of average sea speed/calm

water speed or to assessment of long-term probability of mission performance, with specified ship behavior criteria, or limits, for each mission.

A detailed investigation is needed of the application of these different approaches to specific design problems for different ship types and missions. After extensive discussion among designers and researchers, some tentative guidelines should be developed as to suitable procedures to be used for different ship types on various missions.

References: St. Denis (1976)
Johnson, Caracostas and Comstock (1979).

11. Performance vs Cost (pp. 100-102)

Improving seakeeping performance inevitably involves cost considerations — a longer ship may be more expensive than a shorter one; anti-rolling fins require a larger initial investment; etc. Nevertheless, surprisingly little attention has been given to tradeoffs between performance and cost.

Hence, benefit/cost studies should be carried out for a number of typical cases, involving trade-offs between overall mission effectiveness in all weathers against financial outlay or life-cycle cost. The objectives would be to:

- Obtain direct indications regarding the value of seakeeping research and of applying seakeeping principles early in the design process.
- Develop a procedure that can be routinely applied to new designs in the feasibility and pre-feasibility stages.

Benefit/cost studies in general are discussed by Leopold, et al (1974). A benefit/cost analysis of anti-rolling fins was presented by Gatzoulis and Keane (1977).

SECOND PRIORITY RESEARCH

There are a large number of areas that are in need of further research in order to improve our capabilities to apply seakeeping principles with greater effectiveness to the design of naval ships. A list is given below of those subjects that are recommended for research in the second level of priority.

Environment (p. 16)

Extension of synoptic wave "hindcasts" to the Southern hemisphere and other areas not yet covered.

Generalization of hindcast data in statistical form, leading to simplified specification of wave spectra for design use.

Motion Theory

Filling gaps in motion theory not covered in high priority project No. 4, as discussed on pp. 33-34. In particular:

- End effects.
- Non-linear roll damping.
- Effects of shallow water.

Added Power

Improvement in predictions at all headings to the sea. This involves the following (see pp. 61-67):

- Improvement in experimental methods.
- Development of improved non-linear theory for added resistance at all headings.
- Investigation of propulsion factors and power plant characteristics.

Wave Loads (p. 60)

Systematic exploration of wave bending moment trends on naval ships of various types with size and speed. A current incentive is fuel saving through weight saving.

Clarification of high-speed effects, especially in quartering seas.

Verification of calculated hydrodynamic pressures in waves, over the hull surface.

Further development of theories of impact loads and experimental verification.

Performance Criteria (pp. 108-119)(Workshop Rec's. 12 & 13)

Carry out a fleet seakeeping survey and continue dialog among operators, designers and researchers, making use of the simple instrumentation proposed in high priority project No. 8, particularly for the purpose of establishing more reliable limiting criteria for different:

- Ship types.
- Missions.

Although such surveys, and continuing dialog among operators, designers and researchers, are believed to be of great importance, they have been included under Second Priority Research because it is felt that the development and installation of simple shipboard instrumentation is a basic prerequisite.

Springing

Refinement and extension of available theory, with particular attention to responses in irregular seas. (See pp. 58-60).

Thorough verification of theoretical developments by means of model tests.

Pitching Control (p. 75).

Reassessment of potential for pitch control by means of:

- Passive fins at bow (or better shaped domes).
- Active fins at stern.

Experiment

The application of basic ship motion theory to ever faster ships and to new types of seagoing craft requires continuing experimental checking.

Systematic model testing to verify theory and establish limits of applicability, in terms of ship proportions, types of bow and stern, speed, novel features, etc. (See pp. 24-26, 31-33).

Continuing refinement of techniques for direct experimental evaluation of seakeeping performance (wave loads, wet decks, slamming, added power, steering, etc.) (See p. 45).

Design (Workshop Rec. 11).

Application of systematic calculations and/or experiments to providing guidance to designers regarding trends of seakeeping performance with ship proportions, weight distribution, bow freeboard, and other hull parameters (pp. 33 and 126).

Development of improved routine procedures for application of seakeeping principles and calculations at each stage of the design process (pp. 122-126).

Operator Guidance (pp. 130-137)

Continuing development of systems for guidance of ship operators in the form of:

- Instrumentation, with or without computer backup.
- Catalogs, charts, etc.

Habitability (pp. 117-121) (Workshop Rec. 8).

Continuing collection of data relating magnitudes of motions and accelerations to health and morale of personnel.

Equipment Performance (Workshop Rec. 9).

Continuing collection of data relating magnitudes of motion and accelerations to operation of equipment and systems.

Survivability (pp. 138-141) (Workshop Rec. 14a).

Continuing work on the reliability approach to ship structural design, involving probability aspects of both strength and loading.

Evaluation of forces on and motions of ships drifting in a seaway without power.

Continuing study of stability in following seas and conditions for broaching.

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